High precision silicon piezo resistive SMART pressure sensor

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Abstract. Instruments for test and calibration require a pressure sensor that is precise and stable. Market forces also dictate a move away from single measurand test equipment and, certainly in the case of pressure, away from single range equipment. A pressure ‘module’ is required which excels in pressure measurement but is interchangeable with sensors for other measurands. A communications interface for such a sensor has been specified. Instrument Digital Output Sensor (IDOS) that permits this interchangability and allows the sensor to be inside or outside the measuring instrument.

This paper covers the design and specification of a silicon diaphragm piezo resistive SMART sensor using this interface. A brief history of instrument sensors will be given to establish the background to this development. Design choices of the silicon doping, bridge energisation method, temperature sensing, signal conversion, data processing, compensation method, communications interface will be discussed. The physical format of the ‘in-instrument’ version will be shown and then extended to the packaging design for the external version.

Test results will show the accuracy achieved exceeds the target of 0.01%FS over a range of temperatures.

1. Sensor Structure

The Druck Ltd at Groby, now a division of GE Infrastructure Sensing, has manufactured silicon diffused strain gauge bridge sensors since 1972. The technology employs a silicon wafer into which is etched a stress concentrating cavity and strain gauges are formed by diffusion of dopants into the silicon. Electrical connections are provided by aluminum layers and bonded out to header pins.

This construction of pressure sensor has many advantages not least of which is the high gauge factor of the silicon elements and the ability to construct the elements into a bridge format providing a voltage output with high sensitivity. In addition, silicon is an ideal material having no hysteresis. Sensitivity can be adjusted by etching the silicon to vary the diaphragm thickness.
2. Obtaining high accuracy
Compensation can be used to reduce the repeatable errors in a sensor, the systematic errors. The only approach to non-systematic errors is to reduce them in the design of the sensor.

2.1. Systematic errors
- A second order non-linearity is a feature of this sensor type originating in the non-linearity of gauge factor. Non-linearity magnitude varies with temperature. However both of these effects are highly repeatable.
- Sensitivity and zero offset vary especially between wafers. These errors are easily corrected.
- Sensitivity varies grossly with temperature in a linear fashion and is largely repeatable. As will be seen it may be completely repeatable but difficulty of measuring the extremely small but significant temperature differences limits the view we have of this. Zero offset varies with temperature. The effect is small and varies from diaphragm to diaphragm.

2.2. Non-Systematic Errors
- Silicon as an amorphous material is capable of very low stress hysteresis. However, stresses at the mounting points reflect into the diaphragm and these mounting materials often have complex hysteresis characteristics such as adhesive. Also it may be necessary to use a media isolation mechanism for aggressive media and this can easily introduce pressure and temperature hysteresis. The overall result is temperature hysteresis of sensitivity and zero off set and pressure hysteresis predominantly of zero.
- Noise is of course non-repeatable and is dealt with at the level of the silicon and the measuring electronics. Noise influences performance once during characterisation and then again during use. As it is relatively easy to control this is one area of design deserving close attention.

2.3. Characterisation and Calibration errors
Regardless of the excellence of the sensor the characterisation equipment will stamp its mark on the product performance. Sensor noise and characterisation rig errors and noise will be programmed into the character data store of the sensor as modulation of the true data points. The sensor can never perform more accurately than these errors. The traceable uncertainty of zero and span correction and final calibration must be low enough to meet the overall performance.

3. History of instrument sensors
3.1. 1980s Analogue temperature compensation
Products of the 1980s used sensors packaged with analogue temperature compensation. A network of resistors and thermistors was developed to modulate the bridge supply voltage to correct for the change of sensitivity with temperature.

Non-linearity was corrected by further modulating the bridge supply according to pressure or latterly by characterising and storing the non-linearity at room temperature and applying a correction digitally. Simply multiple straight-line fits almost eliminated the non-linearity at room temperature. However, the temperature compensation was poor and long-term drift was a problem. Sensor character data was stored in the instrument. When sensors had to be exchanged, or remote sensors were periodically connected, the user would have to enter the correct character data for the new sensor.
3.2. 1990 Digital Temperature Compensation
In 1991 we demonstrated the feasibility of digital compensation of room temperature linearity together with span and zero temperature coefficients. Adding a small serial access EEPROM to the sensor enabled the data to be stored in the transducer. For the first time piezo resistive pressure instruments were largely free of temperature influence. Using a multiple cubic fit technique residual non-linearity at room temperature was very small, typically 0.005% FS. With temperature effects reduced to a low level it became easier to measure long-term stability. Stability itself was improved by eliminating the compensation thermistors and was shown to be some 60 ppm per annum or better.

This was good performance but it came at the cost of characterisation equipment that had to pay great attention to isothermal conditions and the instrument electronics needed to be very precise. A large number of sensor connections were also required, limiting use as remote sensor.

3.3. 1996 SOLiD, The people's digital compensation
To make digital temperature compensation available across our product range I needed to consider simplifying the characterisation process, reducing cost and the number of connections and achieving a scalability that would enable the sensor to fulfil varying accuracy requirements. The latter to be achieved ideally without any physical change so as to take advantage of quantity based cost reduction.

In digital temperature compensation to date reducing temperature effects down from 0.22%rdg/deg C to 100 times less than this had been a challenge; an error of 0.01deg C was significant. Some research revealed a simple way of dividing the compensation effort into primary and secondary phases. If the silicon doping were lowered then it was possible to arrive a single series resistor feeding the bridge that allowed the bridge voltage to fall with temperature at a similar rate to that at which the sensitivity rose with temperature. This combination could be used as a ‘primary compensation’ that achieved better than 10 times reduction in span TC prior to any further processing. Now isothermal conditions and electronic measurements could be relaxed by a factor of ten. By using bridge voltage as a measurement of temperature the same wires that conveyed the pressure signal could be used to convey temperature. Memory and bridge supplies were linked such that the connection total was now six rather than eleven. Finally by taking the sensor and using just the primary compensation performance or by adding character data of varying precision a range of instrument accuracies could be achieved from the same sensor. The cost and precision were placed in the instrument electronics and the characterisation. This meant that the same standard low cost sensor could be used in instruments that sold for £250 or £10,000. Characterising a complete but minimised map of temperature and pressure performance and reading this data into the host instrument would now compensate sensor errors. This map would by its nature also contain the relationship between linearity and temperature, which had not previously been characterised.

One drawback was that by inserting the head resistor, and thereby loosing constant voltage excitation, a potential span drift mechanism was introduced. If the bridge resistance changed with time this would cause a change in bridge voltage and hence sensor sensitivity. However, in practice the disadvantages of reduced voltage output for a given supply voltage and this potential drift mechanism were negligible. Stability has been shown to be better than 100 ppm per annum and noise below 1 ppm. With this sensor, named SOLiD (Standard Output Low Doped), 0.01%FS accuracy could readily be achieved including temperature effects. Importantly the sensor with its resistor and character EEPROM was so low cost it could be used in variety of instruments; its performance only determined
by the quality and extent of characterisation data and the electronics of the particular instrument. As I say ‘put the cost where the cost belongs’, in this case in the instrument not the sensor.

Instrument sensor development rested with SOLiD for some time as the value of the development was gained by the launch of low and high value products using the sensor, just as predicted.

3.4. 2002 SMART Sensing, IDOS
Although SOLiD carried its character data with the sensor, a ‘two point matching cal.’ was still required for each sensor to each instrument, which accounted for voltage calibration errors in the characterisation equipment and the instrument. This matching cal. data was automatically recalled when the sensor and an instrument were connected. But the desire to be able to interchange sensors with no concern for calibration problems lingered on. SOLiD was not the panacea for remote sensors on portable instruments.

A new range of portable calibrators was the opportunity to implement a new sensor. As ever technology eventually comes to the rescue and sufficiently high performance, low cost, low power A - D and processor combinations were now available so that a SMART sensor could be made to banish this remaining problem. This new design became known by the name coined for its communication protocol ‘Instrument Digital Output Sensor’ or IDOS (pronounced ‘eyedos’). This sensor would be less universal than SOLiD because IDOS put some of the instrument performance into the sensor so more variants would be required, but the gains were:

- Interchangability without re-calibration
- Sensors can be recalibrated independently of instrument
- The highest possible accuracy because:
  - All the electronics would be characterised at the same time as the sensor
  - Noise would be reduced by eliminating long analogue connections for temperature and pressure signals at characterisation and during use.

If we chose the protocol carefully then all measurands could be accommodated and the opportunity for instruments to quickly and cost effectively have multiple measurands opened up. In this system the sensor identifies itself to the instrument complete with measurand, range and units. The instrument then adjusts its display to show the appropriate format, such as ‘current in mA’ or ‘temperature in degrees C’.

Power consumption was a large factor because the first target product was powered by only by 3 AA cells had to support two internal sensors and one remote, making a total of four processors.
4. SMART Pressure Sensor Design

So the target specification was:

| Parameter              | Specification                                      |
|------------------------|---------------------------------------------------|
| Traceable Accuracy     | 0.05%FS all errors for 1 year, or by option      |
|                        | 0.01%FS excluding stability                       |
| 1 year stability       | Better than 0.01 %rdg                              |
| Supply                 | 2.5 to 3.5V dc.                                   |
| Calibration            | Self contained                                    |
| Signal Interface       | RS232 with propriety protocol, IDOS               |
| Mechanical Interface   | Minimum envelope, mount into plastic moulding     |
| Temperature range      | 5 to 50 deg C                                     |

4.1. Design Approach

Whilst we had size, space and cost constraints we were determined to make the sensor as universal as possible; to establish standards for future instrument performance and to achieve the best measuring performance gathering all our learning from SOLiD.

SOLiD had taught us a number of things:

- Concern of bridge resistance drift with time hampering long-term stability was never dispelled despite low measured drift.
- Noise on the temperature signal needed to be minimised as this creates noise on the pressure reading.
- Pressure coefficient of temperature reading when using bridge voltage as the temperature signal. This could cause an ambiguity of pressure readings.
- The data tabled defined for SOLiD to hold device character and description had worked well.

4.1.1. Selection of bridge Temperature measurement method

To enable accurate temperature compensation it is desired to have the most accurate measurement of bridge element temperature. Two methods were available with the existing silicon design:

- Variation of bridge resistance with temperature
  - Has the advantage of measuring temperature at exactly the right place, the bridge elements
  - Suffers from pressure cross talk. Bridge asymmetry causes bridge resistance to change with diaphragm stress.
- Forward volt-drop across the temperature sensing diode
  - Ten times lower pressure cross-talk
  - But diode signal is not ratiometric

The diode has the advantage of lower cross talk. As a true 20 bit A to D is needed for pressure measurement then by using a second input of this converter to measure diode voltage a resolution of a few thousandths of a degree can be achieved. As both reference and temperature sensor diode are characterised together in this design the lack of ratiometricity is largely eliminated so long as the reference does not drift with time. A high stability reference is selected.
4.1.2. Doping Level/Energisation voltage

The advantage of low doped is associated with primary temperature compensation. A simple head resistor reduces the span TC by a factor of 10. But one penalty is that the energisation voltage must be raised by a factor of four to obtain the same sensitivity, unless a constant current source is used in lieu of the resistor. But a current source can have drift. It is possible to make the current source work from the same reference as the A to D and cancel some of this drift, but life is getting complicated. The series resistor also wastes power.

So the argument veers away from primary compensation with low-doped silicon and towards high-doped silicon. The 5k ohm bridge typical of GE Druck products is normally energised with around 2.5 V so this is an ideal match for a unit to work from 2.5 to 3.5 V. Standard dope also has a five times lower TC of resistance, reducing temperature transient effects and their influence on bridge resistor tracking.

Long term stability concerns regarding drift by charge accumulation thus causing medium and long-term changes in bridge resistance also encouraged the use of constant voltage excitation. Long term stability data from the original digitally compensated standard doped sensors was excellent, better than 60 ppm per annum in a portable environment.

4.2. Data Interface

- RS 232 hardware was chosen because instruments commonly already have an RS232 port for PC connection.
- The sensor could be interfaced directly to a PC
- Much low cost (free in some cases) electronics exist for the interface

GE Druck instruments use a propriety command protocol called DUCI. This language was extended and implemented for IDOS.

4.3. Design Summary

This design aims to meet the target specification by:

| Design feature | Addresses performance Issue |
|----------------|-----------------------------|
| Standard doped, 5 k ohms silicon, constant voltage energisation, diode temperature measurement | Minimised component count for lowest cost smallest size and highest reliability Evidence of high stability Perceived reduction in drift mechanisms Minimised pressure/temperature cross talk for better thermal compensation, esp. low pressures. Minimised inherent non-linearity. Lowest power consumption |
| Two input true 20 bit variable bandwidth A-D converter | Low noise and fast measurements of pressure and temperature signals |
| High stability voltage reference, +/- 3v RS232 interface using DUCI protocol | Avoids long-term drift of temperature signal |
| Sensor data table as used in SOLiD | Ease of interface with instruments and PC |
| Compact mechanical design, rotational torque distribution mounting | Flexible system allows varying degrees of characterisation and a variety of measurands |
| Multi-layer PCA with attention to electrical noise rejection | Suitable for portable equipment, plastic enclosures and multi-sensor applications |
| Compact design and low noise | |
4.4. Packaging

The sensor in its ‘internal’ format should be capable of mounting through a bulkhead inside an instrument. The fixing method should present the pressure connection outside the instrument and be capable of mounting through a metallic or plastic panel. Relatively high torques are applied to the connector to establish a pressure seal, thus with the plastic panel in particular care must be exercised to adequately dissipate this torque to avoid mechanical failure. The diagram left shows that the internal version simply fits into a rugged moulded plastic shell to form the external version. A ‘two shot’ moulding process is used such that the compliant outer moulding adds shock resistance and forms an environmental seal when the case halves are screwed together. A metallic plate dissipates the torque over a wide area of contact.

5. Characterisation equipment

5.1. Development Characterisation Equipment

During sensor development equipment is required to perform experimental characterisations and then to conduct verification tests on sensors. We built our own equipment starting with the SOLID project and refined the performance of this for IDOS. IDOS calibration firmware was specified to accept characterisation data in the same format as SOLID so rig software changes were minimised. The rig needed to be adapted for an RS 232 interface to the IDOS and repeatability and accuracy of the rig were improved by further compensation of the primary standard, a Pressurements 6100 piston gauge.

During development efficiency of production is not the prime concern, but errors of measurement from the reference equipment must be held at very low levels so as to give the correct picture of the sensor under test. We have used primary standards despite the complexity of operation to minimise errors. The exception to this is at very low pressures where differential operation is essential and piston gauges become less accurate. A Ruska quartz bourdon indicator having 70 and 25 mbar ranges is used for very low pressure with its span calibration constantly referred to the Pressurements 6100 piston gauge.

5.2. Manufacturing Characterisation Equipment

Error budgets showed that transfer standards could be used in manufacturing for characterising both the 0.01% and 0.05% variants. The 0.01% variant however could not be verified against the transfer standard. The tracibility of calibration required demanded these sensors be verified against a primary standard.

The primary standards existed but the automatic rigs needed to be built. For sensor ranges up to 200 bar GE Sensing DPI 515 pressure controllers and GE Ruska indicators were employed as the pressure reference. Each transfer standard pressure range spans two sensor pressure ranges, necessitating five controller/indicator pairs housed in three racks. Careful attention is paid to settling times for...
temperature and pressure and novel algorithms look for stability of measurements optimising uncertainty and throughput.

For ranges above 200bar it is necessary to use hydraulic media and an automated dead weight tester. In this way uncertainty is minimised and safety is maintained.

6. Performance results
Measurements to a resolution of 1 ppm were easily achieved. The sensor was extremely quiet. We now started to see a variety of effects that were previously masked but the overall accuracy specification was met with ease. In the short term, even of over the operating temperature range, accuracies of 50 ppm FS are typical. One of the most difficult sensor ranges to make, 3.5 bar isolated, is shown without zero correction and includes two temperature cycles, revealing any thermal hysteresis.

References
[1] Precision Pressure Generation for Test & Calibration, R G Brown. Presented to IoP International Pressure Metrology Conference, April 2005, Portland Place, London UK