Amplified Very-Low Pressure (less than 50 kPa) Piezoresistive Sensors

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Introduction:

Piezoresistive sensors have historically been classified as low performance, especially with respect to zero stability and low pressure (<50 kPa). Recent advances in wafer processing, signal processing, and assembly process-control have allowed a quantum step in the range over which piezoresistive sensors can operate. This paper addresses the steps and capabilities necessary to achieve high performance, low-pressure piezoresistive sensors. Total non-repeatable error of less than 0.05% FS is achievable with proper die design, assembly and testing.

Low Pressure Structures:
A key component of the sensor system is the sensor die itself. A number of structures have been proposed over time to produce low-pressure die. These various structures will be reviewed and the advantages and drawbacks of each will be addressed.

The classic flat diaphragm structure exhibits poor linearity at very low pressure and requires a large collection surface to achieve reasonable outputs. See Figure 1a.

An alternative (Figure 1b) is to fabricate a "bossed" structure with a suspended thicker diaphragm in the center of the diaphragm. The moveable surface then deflects more like a piston deformable plate. This allows force concentration and improved linearity.

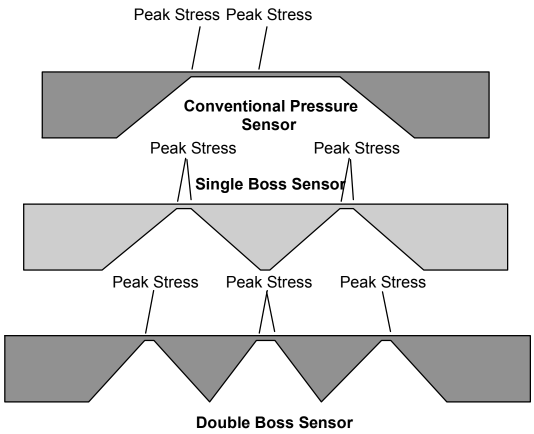

Figure 1a

Figure 1b

Figure 1c

A third alternative is a two-boss structure where resistors are placed at the edge as well as at the center of the diaphragm. This structure has been shown to produce a very high output but can not be always optimized for various geometries. Stress contours are shown in Figure 2. One of the key problems with this type of structure is that the optimum resistor placement requires connecting to a resistor in the center of the active diaphragm. This, in turn, means that the connection has to be a low resistance lead-out such as metal or P+. Both have a tendency to stiffen the structure and metal has been shown to cause thermal hysteresis.

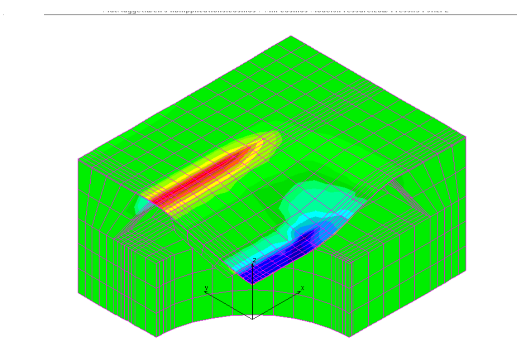

Figure 2 - Peak Stress in a Double-bossed sensor for low-pressure

Because of both the complexities in forming the double-bossed structure and in connecting optimally to the resistors, the double-boss is not the most preferred structure.

As noted above, the flat diaphragm structure tends to be more non-linear than is reasonable in many applications as the pressure is reduced further and further. This is shown in Figure 3 as a comparison against the standard bossed structure with an 80% boss-ratio (Boss ratio = Boss Length/Total Diaphragm Length). What the plot shows is that the boss structure offers about a 10X improvement in non-linearity for the same strain levels in the sensing resistors (same output level, therefore).

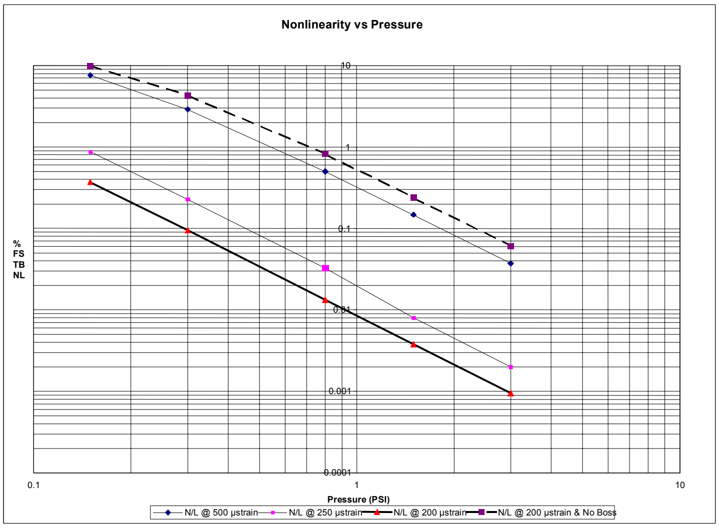

Figure 3 - Nonlinearity vs various strain levels for sensors both with and without a boss.

This shows that with a 2 mm square diaphragm, without boss, if the resistors achieve 200 microstrain, the linearity will be 10% for 10 mbar. As a comparison, with a 80% boss for the same structure, the 200 microstrain output produces a 0.37% nonlinearity. Clearly, the improvements in the structure are substantial.

This structure can further be improved by reducing the diaphragm thickness except where the sensing resistors are as shown in Figure 4. By proper design, the structure can be configured such that 80 to 90% of the stress is conducted thru the sensing resistors.

A cross-section of the device is shown schematically in Figure 4. The resistors are located in such a way that one set of resistors is located towards the outside of the diaphragm while the other pair is located towards the inside. An SEM of the cross-section is shown in Figure 5. The structure as configured offers excellent common-mode pressure rejection for applications such as flow monitoring using pressure drops across an orifice. Typical performance for a 20 mBar (0.3 PSI) part is better than a 20 to 40 ppm/PSI rejection ratio.

The disadvantage of this structure is that, at the lowest pressures, the mass of the stiffening element causes an orientation-dependent output. Both electronic and mechanical solutions are available to address these problems. A structure has been developed that allows a boss of less that 50 microns thickness, compared to a normal device with a 400 micron thick boss. For the same full-scale pressure range, the reduced mass structure has 7 microvolt/g sensitivity vs the normal structure with a 54 microvolt/g sensitivity.

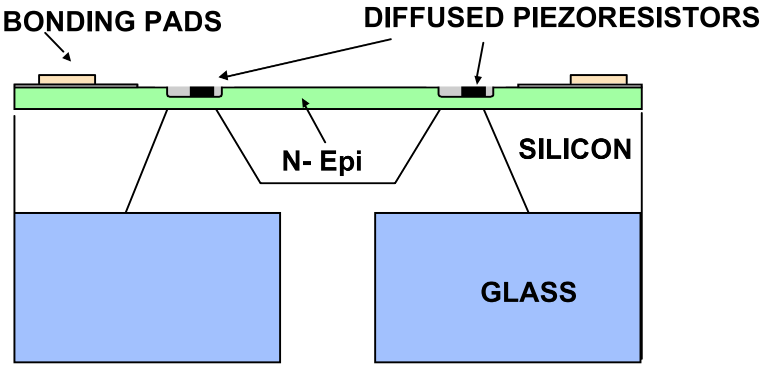

Figure 4 - Conceptual Cross-section of a low-pressure sensor die

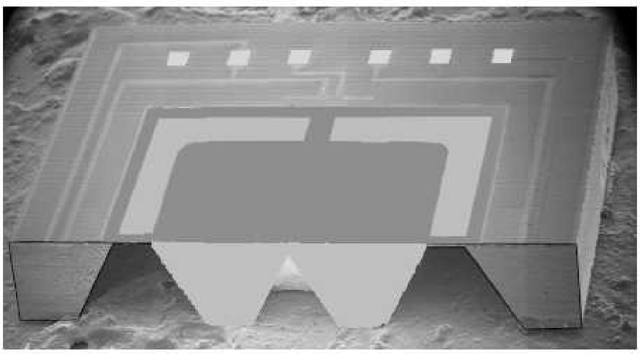

Figure 5 - Actual Cross-section of low pressure die

The center of the diaphragm is thicker than the sensing area. The piezoresistive sensing elements are positioned on the dark-gray beams and the light-gray "L" areas are thinned to allow additional force transduction thru the sensing elements.

The new structure is fabricated thru a two-step micro-machining process (US Patent # **6,093,579**). First, the moat pattern that will ultimately form the boss is etched down about 50 microns. The entire diaphragm area is then opened and the wafer is etched until the silicon is approximately 10 microns in thickness. Because the center part of the boss area began etching 50 microns after the deeper part of the wafer, the result is that the center of the wafer is 40 to 50 microns thicker than the center of the wafer. Computer modeling has been used to optimize this ratio in order to assure that the boss area serves its intended purpose at this reduced thickness.

Packaging:

A second key aspect of the sensor design is in assembly. The piezoresistive element is a stress sensor. If the case stress is not properly managed, then the device will be prone to drift due to package aging.

Critical in this process is the die-attach between the sensor and the housing. In the part reported, the silicon is 400 microns thick, the glass is 500 microns thick and a silicone rubber die-attach of 250 microns is used. In so doing, the stress sensing elements on the silicon-sensing surface is substantially isolated from the case. Issues that have been observed in the past with improper die-attach include thermal hysteresis, pressure non-linearity, and wider temperature performance scatter from die-to-die.

A view of a typical sensor layout is shown in Figure 6. This is a view from a multi-up array of SM5800 which contains both the low-pressure die and amplifying ASIC.

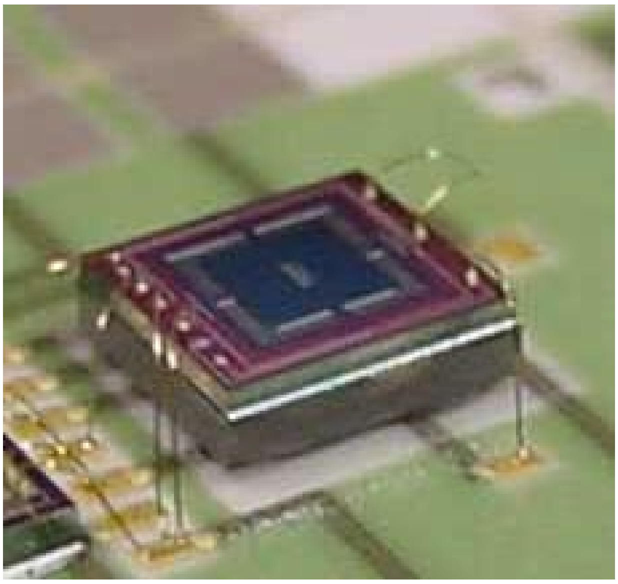

Figure 6 - Picture of Pressure die isolated from the substrate by silicone-rubber die-attach

Amplified Sensor Systems:

The third element of the process to produce very low-pressure sensors is in the signal processing. This is both in the measurement system and in the application. Performance of an un-amplified sensor is largely related to the precision of the measurement during characterization. Analysis of most measurement systems used for pressure sensor calibration will show that typical reproducibility, under the best of circumstances, have about 20 microvolts uncertainty. This means that if the user is trying to calibrate a device with a 20 microvolt per degree C temperature coefficient of zero, then over a 25 C change in temperature by 500 microvolts. The measurement system errors then contribute 4% uncertainty to the measurement. In fact, most sensors have better performance than this and the data acquisition uncertainty, as a percent of the measurement, increases. An easy solution to this problem is to place an amplifier at the measurement site. The trimming approach then subsequently may still dictate the ultimate trimming accuracy. In some cases, the trimming approach has to zero the amplifier's errors and the sensor's errors independently, thereby requiring some ability to externally sense or drive at the sensor's output.

A simplified approach to the signal processing is shown in Figure 7. This configuration is a method adopted and previously reported by Silicon Microstructures several years for a capacitive accelerometer. The key feature of this architecture is that the gain and temperature corrections are performed with digital registers that in turn activate a resistive ladder network to do an analog trim of the sensor/system. The advantage is that the signal path is maintained as a continuous path.

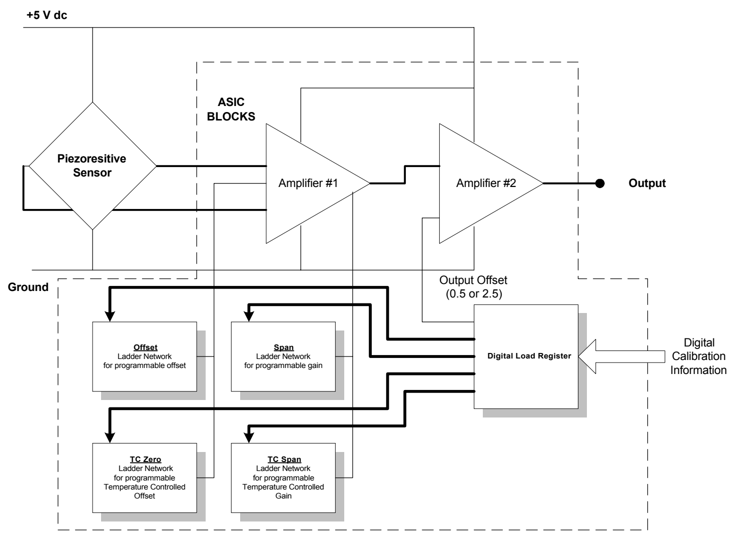

Figure 7 - ASIC Architecture showing the continuous analog signal-processing path from input to output.

A number of amplified sensor systems have utilized a micro-controller structure to convert the signal from analog to digital, then correct the errors in the sensor output and then re-convert the signal back into an analog output. In this way, the ultimate noise-floor is limited to the resolution of the

A-to-D converter. A 12 bit A/D provides 0.025% FS resolution, or a maximum signal-to-noise ratio of approximately 72 dB. As a comparison, the ultimate noise-floor of a piezoresistive pressure sensor is typically better than 95 dB.

One argument in favor of the micro-controller based system is that the part can be reprogrammable. This is particularly true where the sensor-system may have to be reprogrammed at some later date. For expensive systems such as process transmitters, this is particularly attractive especially if replacement of the sensor may be prohibitive. For low-cost systems, the expense of recalibration does not justify the full capability provided by the micro-controller approach.

Amplified Sensor System Performance:
Multiple pressure range parts have been fabricated with the low-pressure sensor and the ASIC.

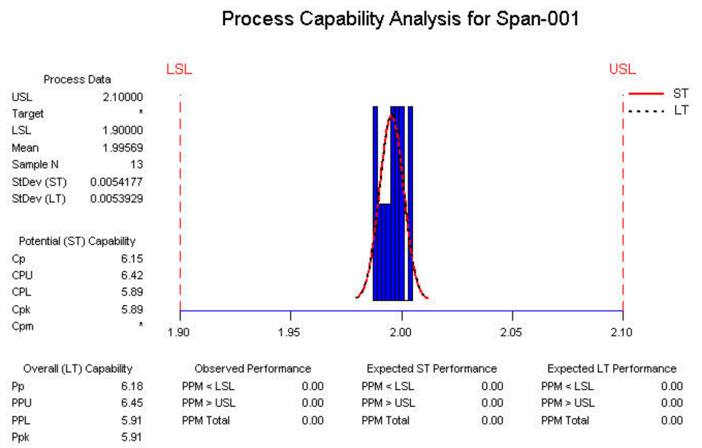

Figure 8 - Initial Span Capability Analysis for SM5852-001

An example of the control and reproducibility of the amplified sensor system is shown in Figure 8. This is a capability study of 13 parts from an SMI 5852-001, showing the tightness of control on span. The normal specification for the part is a +5% FS window. The figure shows an extremely tight distribution and good process control. This control has been achieved due to a good measure of the zero and the output with pressure thru the amplifier during calibration.

The temperature performance is also readily achieved and improved with the addition of the amplifier. The temperature coefficients of zero for several SM5852-008s are presented in Figures 9. The nominal specification for TC of Zero is +1% FS over the 0 to 70 C calibration range. In the sample shown, all parts exhibit 1/2 of the specification range.

The temperature performance of span is shown in Figure 10.

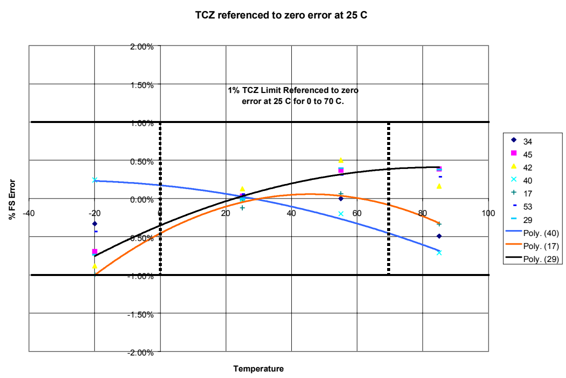

Figure 9 -- Temperature Coefficient of Zero for several SM5852-008 parts

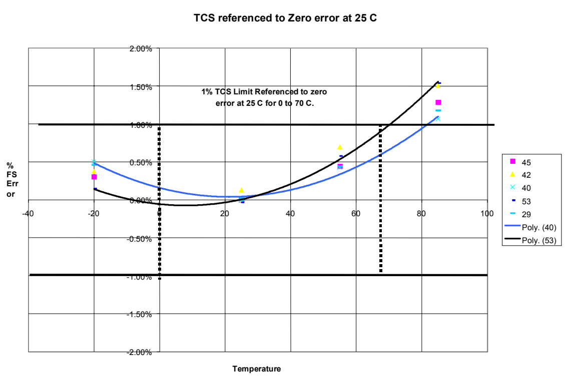

Figure 10 -- Temperature Coefficient of Zero for several SM5852-008 parts

Conclusions:
The combination of a highly sensitive piezoresistive pressure sensor, systematic assembly techniques and electronic trimming produces a reliable, amplified sensor-system.

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