SILICON MEMS PRESSURE SENSOR FOR SPACE

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ABSTRACT

A novel piezoresistive silicon MEMS pressure sensor has been developed for full-scale measurement from 20 bar to > 1000 bar for space propulsion applications. The silicon element has a tubular design with an externally located and highly stable diffused resistor bridge to detect the pressure-induced stress, and fabricated by standard silicon planar technology and MEMS-specific processes, such as silicon fusion bonding and electrochemical etching.

The concept is favourable in rough field applications due to several key properties resulting from small dimensions and deflections, high material rigidity, symmetry, a large output signal, fast pressure and temperature response and low acceleration sensitivity. The overload capability is typically several times the full-scale pressure, since applied pressure mainly generates compressive stress. Long-term and hysteresis effects are minimised by eliminating the package-induced stress due to a relatively large distance from the die attach region to the sensitive region. Total accuracy for a pressure range 700 bar and a wide temperature range from –7°C to 135°C is better than 0.01%FS. Typical hysteresis and repeatability is measured to ± 10 ppm.

1. INTRODUCTION

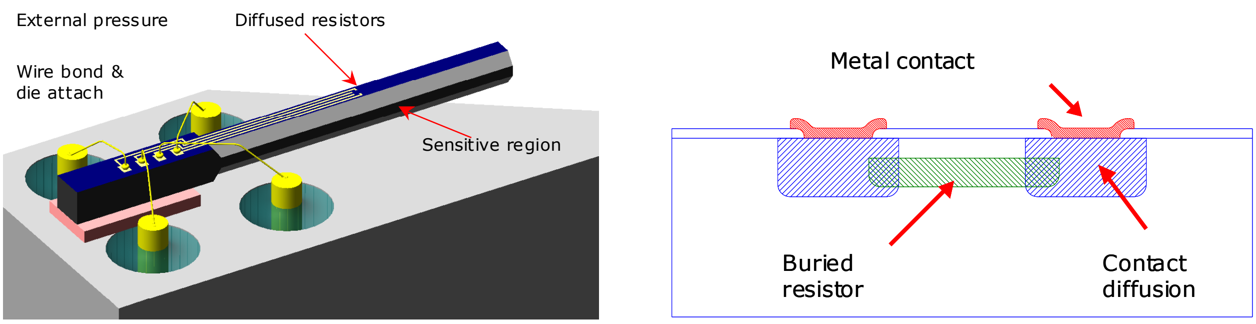
PRESENS main focus is to industrialise a patented concept suited for medium to high pressure applications. Markets addressed with the present concept are oil and gas, space, aerospace, industrial and automotive applications.

In particular, the oil and gas well-head pressure application has similarities with the space propulsion applications in respect of requirements regarding accuracy, long term stability and vibration immunity. Therefore, exploiting the achievements from the high-accuracy oil and gas applications in the space propulsion applications will give significant synergies.

A development program partly funded by ESA is in progress to develop and pre-qualify the silicon technology for space propulsion applications.

2. SILICON TECHNOLOGY

The measurement principle exploited by Presens includes the incorporation of a piezoresistive resistor bridge externally on a tubular silicon structure, as outlined in figure 1 a.



(a) (b)

Fig. 1. Tubular silicon sensing element and assembly concept a), and diffused resistor bridge cross section b).

For a tube the stress in the transversal direction will be twice as high as in the axial direction. The difference in stress between these two directions will be proportional to pressure and can be measured with the piezoresistive resistor bridge. When applying pressure externally to such a tubular element, the design is due to the compressive stress mode inherently robust against overpressure damage.

The sensing element is fabricated by standard silicon planar technology and standard bulk micro machining processes, like silicon fusion bonding and electrochemical etching. The resistor bridge is fabricated by p-diffusions buried by an n-type silicon epitaxial layer, and electrically connected with a standard aluminium metal layer. A schematic cross section of the piezoresistive diffused resistor is given in figure 1 b.

3. SENSING ELEMENT PERFORMANCE

The concept is favourable by having several key properties due to small dimensions and deflections, high material stiffness and a large output signal. Sensitivities has been realized from 10 µV/V/bar to 1 mV/V/bar. Typical full-scale output signal is selected in the range 50 mV/V, and is therefore inherently robust to electrical noise.. The overload capability can be several times full scale pressure.

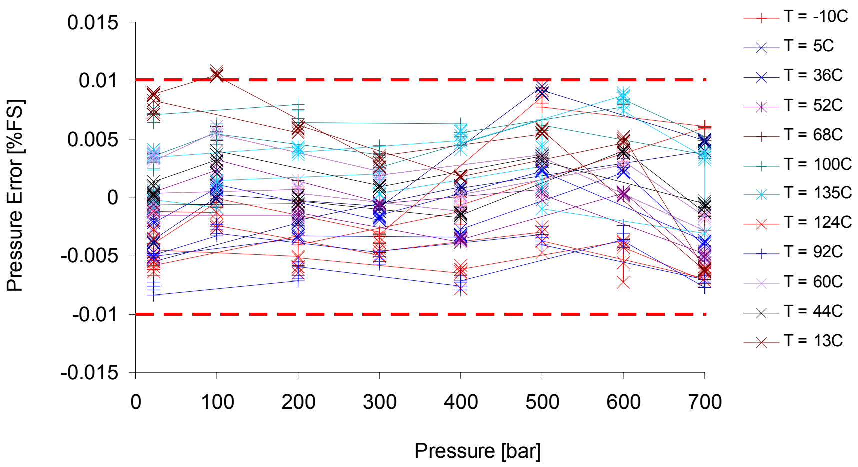


Fig. 2. Pressure error versus applied pressure at different temperatures.

The pressure signal is compensated by a simultaneous temperature measurement in the same resistor bridge, leading to extremely short time constant for temperature compensation of the pressure output. Total accuracy for a pressure range 700 bar and temperatures from –7°C to 135°C is better than 0.01%FS, as shown in figure 2. Typical hysteresis and repeatability for 700 bar pressure range is in the order ± 5 mbar (< 10 ppm). Resolution was measured to approximately ± 1 mbar (1-2 ppm).

The relatively large distance of 3-4 mm from the die attach region to the sensitive region minimises package induced stress compared to conventional diaphragm type silicon sensors were this distance can be in the order 10 times smaller. The package induced stress is very often a significant contribution to hysteresis and long-term drift.

The main influence on the pressure sensor performance from the rough field environment is from acceleration and temperature transients. Typical deviation during a transient of 750 °C/min when submerging the sensor into ice water was measured to approximately 0.20 bar. Acceleration sensitivity is calculated and measured to in the order 1 mbar/g.

These field characteristics enables for high accuracy during dynamic conditions, which is essential to maintain laboratory accuracy in rough field environments.

The long-term stability in a rough environment well-head application is analysed by comparing the sensor output from two identical pressure and temperature sensors installed in the same location in a specific oil well. The sensor output comparison was done approximately 3 years after installation during identical pressure and temperature exposure, and the pressure difference is limited to less than 0.05 bar as indicated in figure 3. From this test, the long-term stability is estimated to approximately ± 0.003 %FS/year.

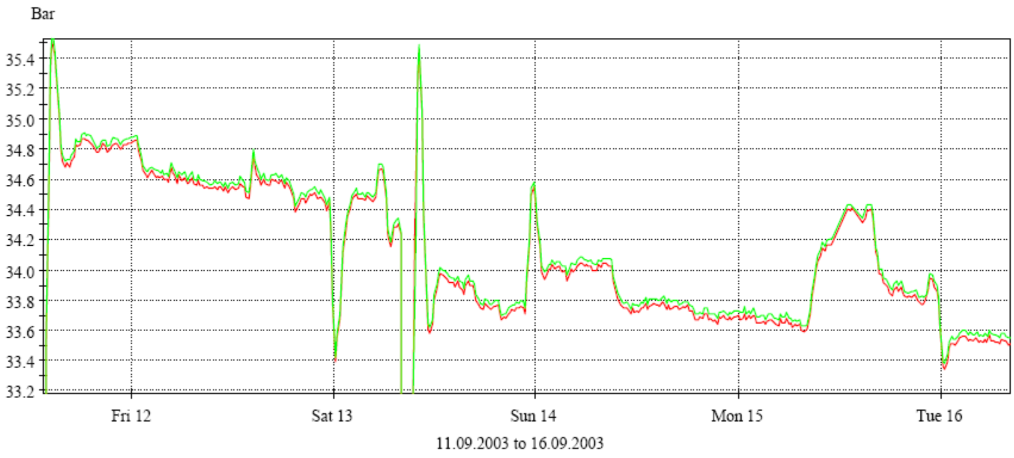


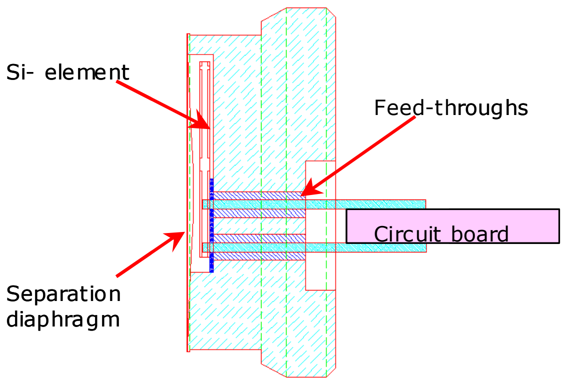
Fig. 3. Field stability.

4. HOUSING

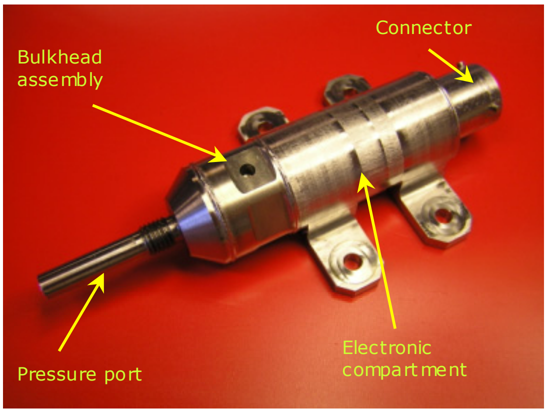
4.1 Media isolated housing

The sensor housing material is very often application specific. The sensor housing has been realised in different qualities of stainless steel and titanium.

For the space sensor, the sensing element is packaged in an all electron beam (EB) welded titanium housing, and includes 4 conventional high-pressure electrical glass-to-metal feed-through between the pressurised sensing element compartment and the hybrid circuit compartment. The sensing element is attached to the housing by an adhesive in the non-sensitive wire bond pad region, and electrical connection is done by wire bonding.



(a)



(b)

Fig. 4. Media isolated packaging concept with conventional feed-through and separation diaphragm a), and complete pressure sensor with conditioning and interface circuit b).

The sensing element is protected from the media by a dual separation diaphragm fabricated in the same corrosion resistant material. The separation diaphragms are welded to the housing using EB-welding, and finally, the sensor cavity is filled with silicone oil and sealed by using a resistance welded ball. The pressure drop across the diaphragm is limited to 50 ppm of applied pressure, which is eliminated by compensation during calibration. A cross section view of media isolated package concept is indicated in figure 4 a.

Total sensor mass of the space sensor is in the order 125 gram. The hybrid circuit compartment is hermetically sealed, and electrical interface is by hermetic connector according to ESA-requirements. Complete space pressure sensor is shown in figure 4 b.

4.2 Small diameter sensor

For inert fluid applications protection of the sensing element can be eliminated leading to an alternative packaging concept were the tubular silicon element can be used as the electrical feed-through directly.

This alternative packaging concept is based on potting the tubular silicon element into a hole in the steel housing bulkhead, as indicated in figure 5. Potting material depends on the specific application, but glass or epoxy are candidates. This concept enables for total sensor diameter from 4 mm.

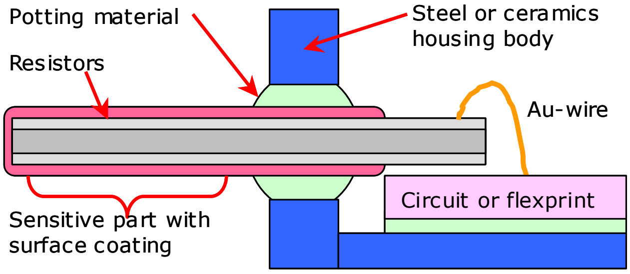
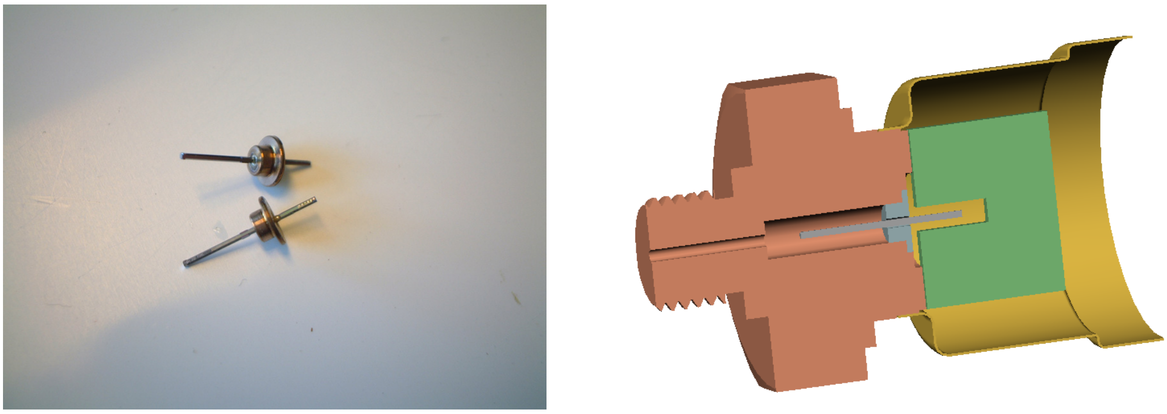


Fig. 5. Small diameter packaging concept.

A prototype version of the silicon MEMS sensing element glass-melted into a metal disk is shown in figure 6 a. The metal disk diameter is 5 mm and complete length 7 mm, enabling for small size and compact integration of the sensor into the system. A schematic cross section of a complete sensor concept with the glass-sealed sensing element sub-assembly as an integrated part is shown in figure 6 b. The sub-assembly can be welded into the pressure port by electron beam, laser or resistance welding techniques. Total mass starting from less than 30 grams, depending on the actual conditioning circuit configuration.



(a) (b)

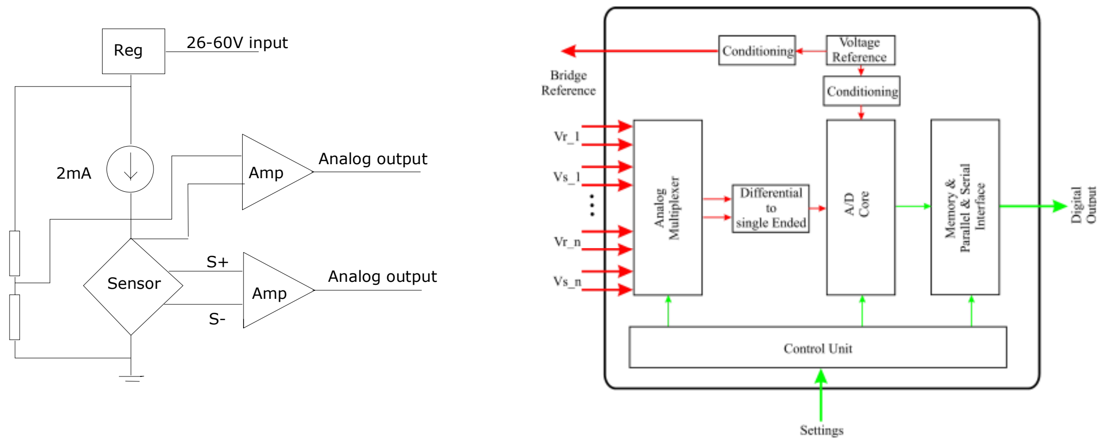
Fig. 6. Sensing element mounted in metal disc using glass-melting process a) and complete in-line sensor concept b).

5. CONDITIONING CIRCUIT

5.1 Analog interface circuit

The sensor includes a hybrid circuit for amplification and individual functional calibration. The dual channel circuit schematics as indicated in figure 7 a enables for precise measurement of sensor bridge output voltage and resistor bridge total resistance, which both varies with pressure and temperature. Conventional instrumentation amplifier scheme with chopper modulation of the differential bridge signal is used for high stability.

The pressure signal temperature influence is compensated to the first order by using constant current excitation. Thin-film resistor networks are included to compensate individual sensor element offset and sensitivity variations.



(a) (b)

Fig. 7. Analog conditioning and interface circuit measurement set-up a) and digital interface ASIC block diagram b).

In order to obtain high accuracy, additional linearisation and temperature compensation is necessary in external system software. Output signal from sensor is 0 - 5 V. Total accuracy for the complete sensor is better than 0.1 %FS.

Main components used in prototype units;

- Precision thin film resistors and resistor networks
- Precision operation amplifiers (Linear LT1013)
- CMOS switch (Intersil HI9P303-P)
- Linear regulator (National LM117H)
- Power MOSFET (Intersil IRFF9130)

The analog hybrid circuit is realised on a double-sided ceramic substrate using naked die integrated circuits. For flight models the components will be replaced by radiation hardened versions of the same component

5.2 Digital interface circuit

The development of a digital ASIC (Application Specific Integrated Circuit) is initiated as a product enhancement, motivated by smaller dimensions and mass, improved functionality, improved accuracy, improved production logistics due to fewer components, etc.

The development of a highly accurate, radiation hard digital sensor interface circuit is based on existing mixed signal remote sensor interface chip with 10 bit effective resolution [1-4]. The main challenge in this design is to improve the effective resolution to 14 bits without compromising the radiation immunity.

The block diagram of the digital interface ASIC is shown in figure 7 b. It consists of a differential analog multiplexer, a differential to single ended stage, a 14 bit ADC core and a parallel / serial digital interface. Differential input voltages Vs and Vr are converted to single ended voltages consecutively and are digitised through the ADC. The bridge reference voltage has an upper rail equal to the power supply.

The following addressed areas will contribute to give European companies a competitive edge; increased accuracy, reduced size and mass, reduced power consumption, bus interface to satellite is likely to be less complex than analog measurement channels, pressure and temperature output on same digital bus, reduced harness (reduced total weight), circuit designed and manufactured in Europe, the Presens space pressure sensor will be a 100 percent European product, introducing multiplexer on analog input enables the possibility to include several (2 - 3) sensing elements in order to obtain measurement redundancy, possibility to store individual parameters in circuit memory will improve logistics requirements and traceability, possibility to calculate pressure and temperature locally, and finally, generic mixed signal component might find its usage in other space applications with minor modifications.

6. CONCLUSIONS

Highly accurate piezoresistive pressure sensors have successfully been developed using standard piezoresistive diffused resistor technology. Due to important key properties like a large output signal, low acceleration sensitivity, fast pressure and temperature response, and over pressure robustness, this sensor will be able to maintain laboratory accuracy in rough field environments.

For space propulsion application a dedicated all-welded titanium housing construction and analog hybrid conditioning circuit solutions is developed and pre-qualified. This program is continued in a validation/pre-qualification program of technology and fabrication process enabling for formal industrial space qualification.

The development of a digital interface ASIC (Application Specific Integrated Circuit) has been initiated as a product enhancement, motivated by smaller dimensions and mass, improved functionality, improved accuracy, improved production logistics, etc. The ASIC is developed by the Greek institute DUTH and funded by ESA under GSTP.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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