Absolute Pressure Measurement using 3D-MEMS Technology

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ABSTRACT

The use of 3D-MEMS processes has created yet another new breakthrough. Extremely small silicon capacitive absolute pressure sensors can now be realized by utilizing the same MEMS technology that has been in production for many years. The applications where absolute pressure measurement has not been possible due to size or current limitation can now be solved effectively.

The new breakthrough has enabled VTI Technologies to offer extremely robust capacitive pressure sensing elements with low current consumption and excellent performance. The hermetically sealed elements are made of single crystal silicon, which is close to perfect elastic material. These features along with its compact size make it possible to extend absolute pressure measurement to completely new areas such as wellness and safety. The same capacitive sensing element can also be used for battery-less measuring systems like tire pressure monitoring.

The development of a complete sensor component is underway and will only be 6 mm in diameter and 1.7 mm high. This device will be capable of detecting the smallest barometric pressure change, which enables extremely accurate weather forecasting and altitude measurements. The supply voltage (2.4 – 3.3V) and current consumption (0.5 - 50µA) make it easy to integrate into products like outdoor equipment and sports watches.

The excellent accuracy and resolution enables algorithms not seen in consumer weather stations or outdoor equipment before. In a sports watch application, the new sensor component can provide a resolution better than 0.2m (2PA) and consume less than 30µA when operated continuously at a rate of 2 times per second. When increasing the update interval to 2 seconds, the current consumption can be reduced to less than 10µA.

The absolute pressure sensor elements are available today and can be soldered directly onto a PCB as a SMD component. The development of a complete sensor component (SCP1000) will be launched in 2005.

Keywords: MEMS, capacitive, absolute, pressure sensor, barometric, altimeter.

1 3D-MEMS TECHNOLOGY USED FOR PRESSURE SENSORS

3D-MEMS is an optimized combination of technologies to achieve the best performance at the smallest size and lowest power. The technologies include wet and dry etching, capping with wafer bonding and glass insulation, electrode feed through structures and contacting for wire bonding and soldering. Unlike some other MEMS (Micro Electro Mechanical System) technologies, VTI offers real 3-dimensional structures (Figure 1), not just thin films on top of a silicon wafer. This gives flexibility in optimizing electrode insulation, stress minimization and capacitance dynamics for performance. Unlike piezoresistive pressure sensors, the relative capacitive change over the measuring range is typically 30-50% making it easy to measure, thus enabling high signal to noise ratio and accuracy even at low current levels.

Figure 1: VTI's 3D-MEMS absolute pressure sensor element manufactured on 150mm wafers

The glass insulation in use is relatively thick and gives high isolation resistance (low leakage current) and low stray capacitance. The two silicon wafers are anodically bonded together resulting in a hermetically sealed structure, where no chemicals or particles can intrude into the space between the capacitive electrodes. The mechanical material in use is single crystal silicon giving hysteresis free operation (no plastic deformation) and excellent over-range and shock performance. The sensor can withstand a pressure significantly higher than 10 times the measuring range. The excellent long-term stability of pressure sensors made in this technology was already proven in older sensor designs in the 1980's.

2 MANUFACTURING OF 3D-MEMS

To define the optimum shape and size of the APS4 pressure element, VTI had to perform many simulations in order to satisfy all the design parameters.

While the footprint of 1.4 x 1.4 mm^2 offers the best optimization for the length and width, the height has been optimized for different applications. The height of 0.85mm was chosen for high accuracy wire bondable applications. Taller devices are required to compensate for any mechanical stress related to direct soldering. The height of 1.25mm was chosen for both the 8 and 25 bar elements.

2.1 Transfer Function

The size of the element is the most important factor to keep a high dynamic measurement range. Hence the size was optimized to keep the capacitance range as high as 7pF for 0bar and 14pF for full scale pressure. This was achieved by an extremely small distance between the two capacitor plates with a nominal gap of 1µm. The passive parallel capacitance was kept small by using a thick glass layer between the upper and lower silicon layers. Silicon feed-throughs are used to make the necessary contacts. This technique provides a good active to passive capacitance ratio. The transfer function follows the equation:

$$C = C_{00} + \frac{C_0}{1 - p/p_0}$$

whereas C_0 is large compared to C_{00}. The realized values are in the range of: C_{00} = 1pF and C_0 = 5 pF. Figure 2 shows the measurement results of the first 1.2 bar prototypes.

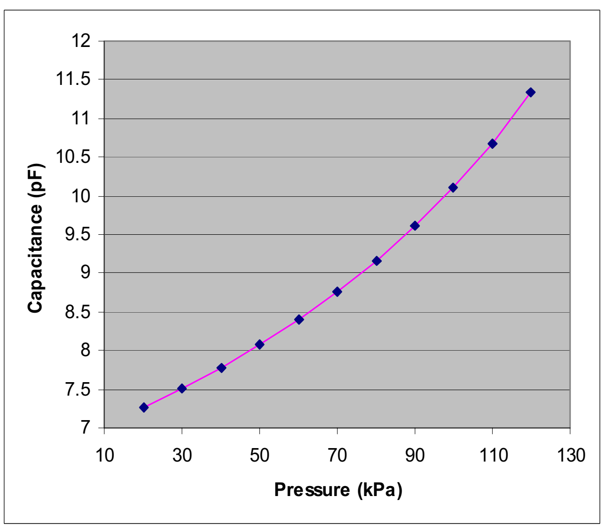

Figure 2: Transfer function of APS4 of first prototypes (measured results)

Reflecting the transfer curve over temperature provides the perspective that temperature compensation wouldn't be necessary for this type of element. The main reasons for this positive behavior are the small C_{00} impact and the fact that silicon is used as a conductor. This advantage needs to be preserved by using appropriate signal conditioning and mounting techniques to avoid thermal related stress to the sensing element.

2.2 Linearization

The linear behavior of the APS4 element is in line with the parallel plate model according to the following equation:

$$p = p_0 * (1 - \frac{C_0}{C - C_{00}})$$

Figure 3 shows that there is only a small deviation between the transfer curve of first sensor prototypes and the ideal parallel plate model. The maximum deviation is less than 20Pa (0.2mbar).

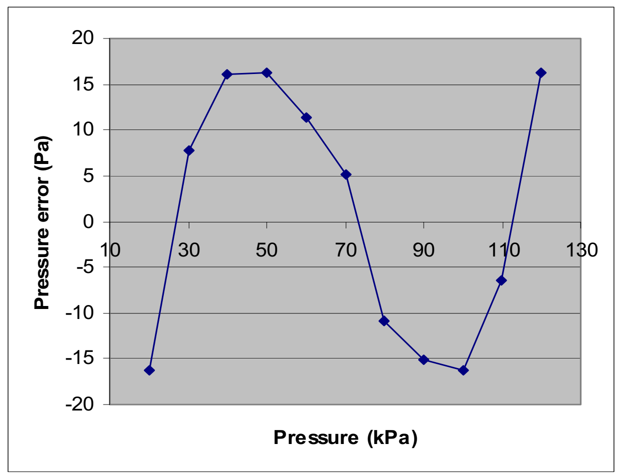

Figure 3: Difference between parallel plate model and Sensor Output

The APS4 sensor element gives engineers the ability to design ultra low current consumption circuits due to the high parallel resistance, which is greater 10 Gohm.

2.3 Optimizing the Diaphragm

The diaphragm can be dimensioned in such a way that sensor elements from 1bar (20µm) to 30bar (80µm) can be realized. By using wet etching, the height of the diaphragm can be processed quite accurate. The height or thickness of the diaphragm is determined by the full-scale pressure range. The gap is always kept at 1µm to remain with the same dynamic range for all the potential variants of this concept.

Underlying the design of the diaphragm was a requirement to avoid any signal changes caused by centrifugal force as well as any mechanical shock caused by rough disturbances. For that reason, the diaphragm has to be optimized in order to make a good compromise for the transfer function.

2.4 Designing for Long-Term Stability

The long-term stability of an absolute pressure sensor depends on the seal of the anodic glass bond, which can only come from highly controlled production processes. VTI has more than 20 years of experience in glass bonding technology. Glass is a well known material but it has some specific characteristics like outgasing and absorption of residual gas, which could change the internal pressure of the sensor.

To ensure good long-term stability, a wet etched gas reservoir was connected to the reference pressure gap. The difficulty in the given design was to find any space in the optimised element structure. The positioning of the vacuum reservoir is shown in figure 4 schematically and in figure 5 as a cross section in silicon.

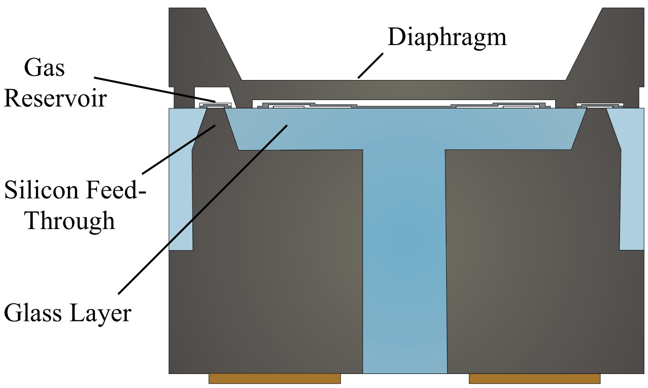

Figure 4: Schematic cross section APS4

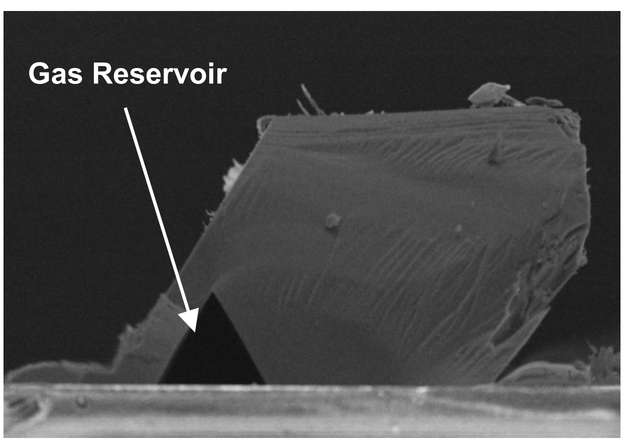

Figure 5: Vacuum reservoir for long term stability

2.5 Pad Location

VTI developed their first pressure sensors with the contact pads co-located on the same surface as the diaphragm. The contact pads were consuming space on the surface and it was difficult to protect them against aggressive media. To reduce the size of the element, the pads were moved to the bottom by adding a glass isolator in the middle of the element as shown in figure 6. The glass is structured in such a way that the offset capacity value is kept as small as possible.

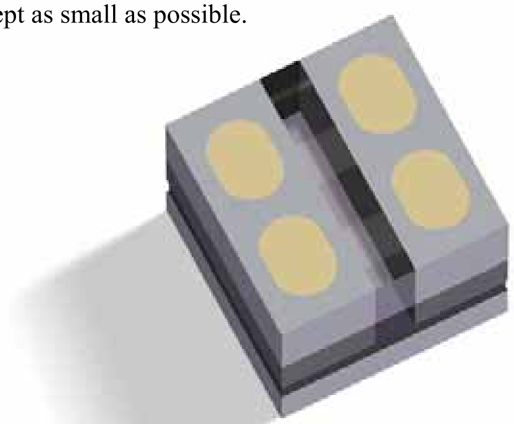

Figure 6: VTI's APS4 pressure element showing contacts

3 PRICIPAL OF OPERATION

The principle of operation of VTI's pressure sensors can be seen in Figure 7. The outer pressure relative to the reference pressure inside the cavity between the silicon wafers causes a force on the membrane of the top wafer, bending it towards the bottom electrode. The elastic membrane acts as force gauge. The displacement of the membrane is detected as a change in the value of the capacitor (C) between the membrane and the counter electrode. The function 1/C is a fairly linear measure of the force acting on the membrane and it can easily be linearized with a simple polynomial for highest linearity.

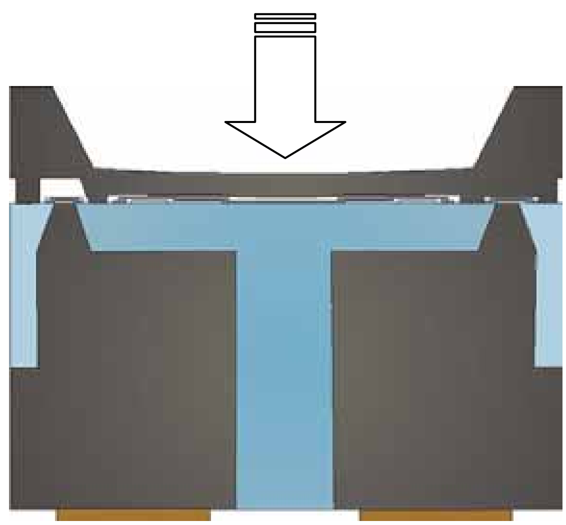

Figure 7: APS4 diaphragm under pressure

4 FEATURES OF VTI'S PRESSURE SENSORS

VTI is introducing a low-power absolute pressure sensor concept mainly intended for battery operated handheld devices. Measuring ranges extend from barometric (100kPa) to 25 bar (2500kPa). The output is digital over SPI (Serial Peripheral Interface). The SMD (Surface Mount Device) component SCP1000 is as such intended for non-corrosive environments, but being only 6.1mm in diameter and 1.7mm in height (Fig. 8) is easy to protect from aggressive media. The sensor component has a circular vertical wall for O-ring sealing, a feature important in a humid environment and when measuring in liquids like water.

Figure 8: VTI's low power pressure sensor component SCP1000 (ϕ = 6.1mm, h = 1.7mm).

The more detailed description of the features below is much related to the barometric sensor for the range 30…120kPa, corresponding roughly to -1000…+9000m in altitude. For other ranges the accuracy parameters roughly scale with the range.

SCP1000 has different measurement modes for optimum performance in different applications that require different resolution, speed and power consumption. All modes operate with at least 2.4…3.3V power supply. In the high-resolution mode the barometric sensor has a resolution of better than 2Pa, corresponding to about 16cm in an altimeter application at sea level. This resolution can be achieved with a twice per second update rate and at 20µA power consumption in continuous operation. In the high-speed mode the resolution is about 5 times worse and the speed 5 times higher.

To save power there are two options. One of them is to use the low power mode, where after each measurement the sensor goes into stand-by and consumes 3 - 4µA. In this mode the sensor stays ready for the next measurement command over its digital SPI interface. Switching off power between measurements can even save more power. Hereby the wake-up time being around 10ms is important.

SCP1000 has excellent accuracy and linearity. Under normal outdoor conditions for hand-held devices, 10…40°C, an accuracy of better than 2m can be reached at sea level. In a wider altitude and temperature range, i.e. 0…3000m and -20… +70°C, an accuracy of 30m or better can be reached. Hereby the non-linearity, being less than 10cm, is insignificant.

The SCP1000 includes a temperature sensor with 0.1°C resolution and ±1°C accuracy.

5 APPLICATIONS

There are numerous applications for the SCP1000 product family but the main focus area is wellness, sports and outdoor applications. In particular, handheld devices such as sport watches and diving computers, where a combination of small cost effective designs, low power, reasonable resolution and accuracy are important. The SCP1000 works well as an altimeter and is a perfect compliment to any GPS (Global Positioning System) signal for navigation systems.

The sub-meter altimeter resolution and 1m accuracy (under normal conditions) provides sports and fitness users a precise calculation of the accumulated risen height for a particular training session. On the other hand the high-speed mode and good performance in a wide altitude and temperature range give new opportunities in skydiving, paragliding and similar applications.

In sports and outdoor activities the barometric sensor can be used to forecast local weather and measure the oxygen pressure through the total air pressure.

Small and accurate low power pressure sensors are also finding their way to the medical field. Blood and brain pressure sensing are obvious applications. The barometric pressure sensor through its high resolution is an excellent fluid level. Its resolution is about 0.1mm water.

The 16 bar version of SCP1000 is intended for diving computers and water depth sensing. Of course it can be used in industrial fluid level applications as well. Another application area is pressure measurements in pneumatic systems, where the sensor through its low power consumption could be wireless or even be built into a batteryless transponder.

REFERENCES

[1] Jens Thurau, Dr. Jaakko Ruohio, Silicon Capacitive Absolute Pressure Sensor Elements for Battery-less and Low Power Tire Pressure Monitoring, AMAA 2004