3. Capacitive Pressure Sensor

3.1 Capacitive Pressure Sensor Design

In a capacitive pressure sensor, the flexible diaphragm serves as one electrode of a capacitor, whereas the other electrode is located on a substrate beneath it. The average gap between the electrodes, and thus the capacitance, changes as the diaphragm deflects in response to an applied pressure. The theory behind capacitive sensors is relatively simple. The capacitance between two parallel plates with a surface area *A*, separated by a distance *d* by a dielectric with dielectric permittivity ε, is given by:

$$C_0 = \varepsilon \frac{A}{d} \tag{1}$$

Capacitance changes ΔC related to the electrode displacement Δd can be approximated by the derivative $\partial C / \partial d$ if Δd is much smaller than *d*:

$$\frac{\Delta C}{\Delta d} \approx \frac{\partial C}{\partial d} = -\varepsilon \frac{A}{d^2} \tag{2}$$

If the electrode movement is not parallel, or if the capacitance change is caused by deflection of a part of the electrode, then the total capacitance change should be calculated by integrating over the entire deformed dielectric space. We can see from the Expression (2), that the relative change of capacitance ΔC/C is not linear with respect to the deformation and thus the pressure, but the relationship is reproducible and its full scale value can be 20 – 200 %. To design capacitive sensors with high sensitivity, it would suffice to make a plate area large and a gap distance narrow. However, technological factors such as membrane dimension, fabrication accuracy and reproducibility, and damping of the membrane movement if the gap is filled with gas or liquid, limit these values.

For semiconductor pressure sensors the movable electrode is often a thin, square silicon bulk-micromachined membrane that is deflected by a pressure applied to it. The concept, illustrated in Figure 3.1 represents a group of capacitive pressure sensors where the membrane is etched from a silicon wafer using isotropic or anisotropic etching.

Figure 3.1. Bulk-micromachined capacitive pressure sensor with glass substrate.

The gap of the capacitor is usually defined on the silicon wafer. The thickness of the membrane usually varies from 1 to 2 µm that of the gap varies from 1 to 5 µm. The silicon diaphragm is electrostatically bonded to the Pyrex glass, or other substrate. If the substrate is an electrically non-conductive material, such as glass, a metal layer serving as a capacitor fixed electrode must be deposited on it.

A similar solution uses a structure with an ultra-thin diaphragm with a centre boss [ZHA 90, ZHA 94]. This structure, shown in Figure 3.2, has several advantages. This solution offers very high sensitivity by using an ultra-thin diaphragm. A nearly parallel capacitor obtained by using the centre boss enlarges the operating range and yields improved linearity.

An improvement in terms of linearity can be obtained through another design based on a centre clamped diaphragm [OMI 97]. The sensor with a silicon-glass structure is fabricated by batch-fabrication process.

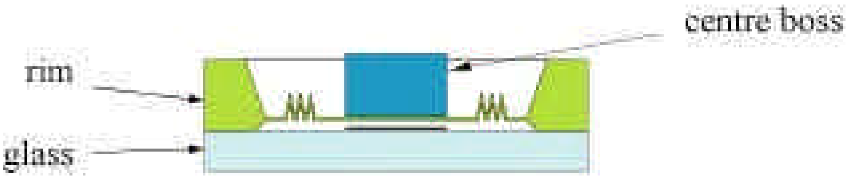

Figure 3.2 Bulk-micromachined capacitive pressure sensor with centre boss.

Some transducers use silicon as the substrate. In this case, the two conductive silicon wafers are bonded together with a dielectric spacer that serves for the electric insulation between the electrodes and for the gap thickness definition. Such a solution reduces the thermal drift of the sensor and simplifies the processing. A possible solution of such a sensor is shown in Figure 3.3. The device consists of two silicon substrates fusion bonded together with a silicon dioxide passivating layer sandwiched between them. The silicon wafers form both the mechanical part and capacitor electrodes and therefore no metallized electrodes are required.

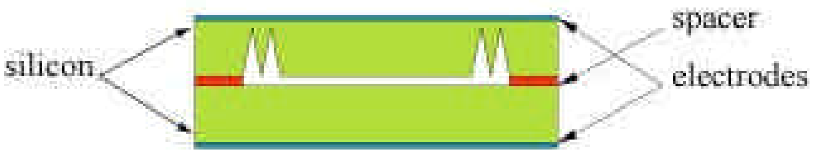

Figure 3.3 Bulk-micromachined capacitive pressure sensor with silicon substrate.

The top silicon substrate has been etched to form corrugations in the diaphragm to define the behaviour of the diaphragm under pressure. The thickness of the SiO_2 layer determines the gap between the electrodes and therefore, along with a bonded circumference around the diaphragm, the base capacitance of the device. Both free surfaces of the bonded wafer pair are coated with a metal layer enabling the electric contact to electrodes. Relatively thick membrane corrugated on the edges reduces the degree of bending across the top electrode and thus improves the sensor linearity.

Surface-micromachining techniques provide a possibility to deposit various materials (polysilicon, SiO_2, Si_3N_4, Al_2O_3, etc.) on the silicon wafer and selectively etch off part of the material to construct mechanical structures as membranes, beams or cavities on the top of the wafer. An example of a surface-micromachined capacitive pressure sensor is shown in Figure 3.4. In this example, the movable electrode of the transducer is made of polysilicon, the fixed one is realized as a metallized surface of the silicon substrate. In this structure, no bonding process is needed.

Figure 3.4 Surface-micromachined capacitive pressure sensor.

Figure 3.5 shows an early attempt to integrate a capacitive sensor with an FET circuit. The pressure difference between two faces of the membrane will cause the distance change between the ring and the pedestal, thus the change of ring-to-pedestal capacitance, which is the input capacitance of an FET built into the silicon membrane.

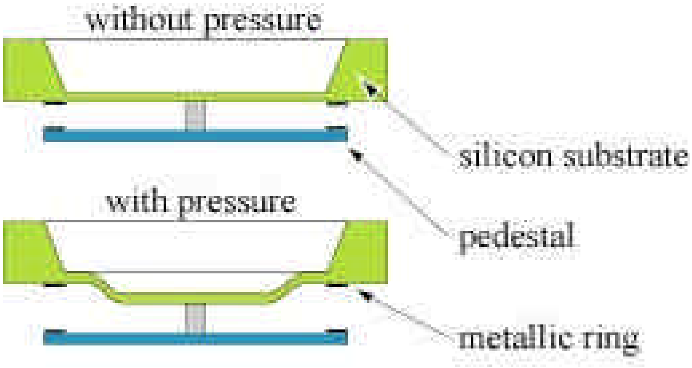

Figure 3.5 Capacitive pressure sensor with a pedestal.

A concept of a pressure sensor working in a touch mode has been proposed by [CHO 92, KO 96]. This mode of operation extends the useful operating range of the device beyond the full-scale deflection that is conventionally defined by the point where $\Delta C = C$ (see Figure 3.6).

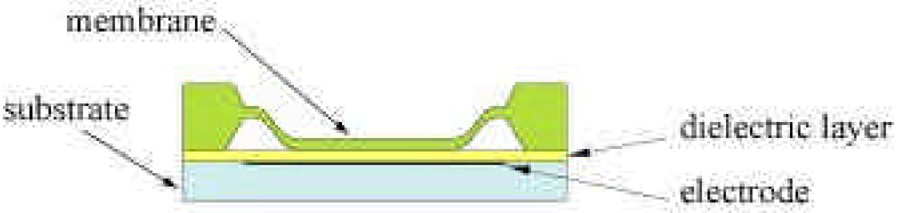

Figure 3.6 Touch mode capacitive pressure sensor.

As long as the electrode is electrically isolated from the membrane, such as by an intervening thin film of dielectric material, the capacitance keeps raising even beyond the threshold at which the diaphragm touches the substrate beneath it. The operating range can be thus extended by the factor of two or more [KO 96]. A method for including the touch-down effect into behavioural models of Microsystems is described in [PET 99].

3.2 Signal Conditioning of Capacitive Pressure Sensors

In order to obtain electrical voltage or current output from a capacitive pressure sensor, signal conditioning circuit that can convert the relative capacitance change to the voltage or other electrical signal is needed. There are many circuits that can convert a capacitance change into a voltage, frequency, or pulse width modulation.

Circuits based on impedance bridges are often used for this task. A typical circuit of this category is shown in Figure 3.7.

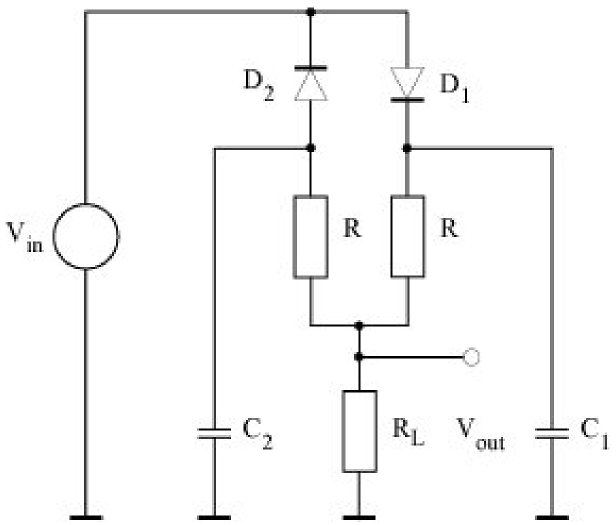

Figure 3.7 Capacitor to voltage converter bridge.

A square wave generator E_{inp} drives the network at frequency *f* and the output voltage is:

$$V_{out} = V_{in}\, f\, \frac{RR_L(R+2R_L)}{(R+R_L)^2}(C_1 - C_2) \qquad (3)$$

The excitation frequency should be reasonably high so that the sensor impedance is as low as possible. The frequency should also be low enough for an easy circuit design.

Impedance bridge based circuits of this type and its derivatives, as well as other AC bridges, have been successfully used in industry. The disadvantages of this approach are the limitation of the full-scale output range due to non-linearity and the reduction of the sensitivity and resolution due to stray capacitances.

Another way to obtain the information from the sensor output is using capacitor-controlled oscillators that convert capacitance changes into frequency or time period changes. A possible solution of this type of conversion is schematically shown in Figure 3.8. In this circuit, the capacitor determines the frequency of the oscillation and an FM signal proportional to pressure may be obtained.

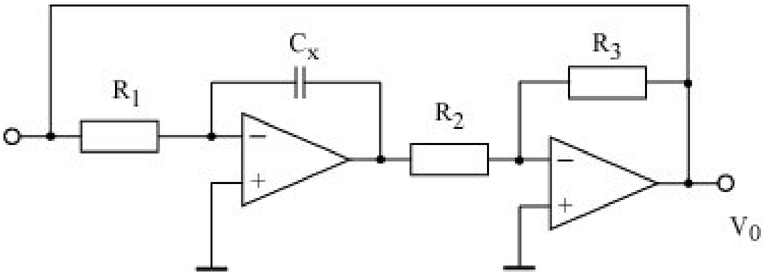

Figure 3.8 Capacitor to frequency converter.

Alternatively, a relaxation oscillator using RC to determine the time constant can be used for capacitance to time conversion. The major problem of these solutions is the stability of the frequency or period when no pressure is applied and the temperature drift. The possible scheme to overcome these difficulties uses a pressure insensitive capacitor as the reference to cancel the environmental drift.

Charge measurement circuits can also be used in liaison with capacitive sensors. In this case, a fixed voltage V, is applied to the capacitor C. If the charge stored $Q = CV$, is kept constant, capacitance variations due to pressure can be converted into voltage variations. A switched capacitor circuit is one of the possible solutions of this conversion.

Another interface circuit that offers high sensitivity and immunity from parasitic capacitance is illustrated in Figure 3.9. This is basically a switched-capacitor charge integrator which utilizes a two-phase clock to compare the variable sense capacitor C_x, to a reference capacitor C_R [PAR 90].

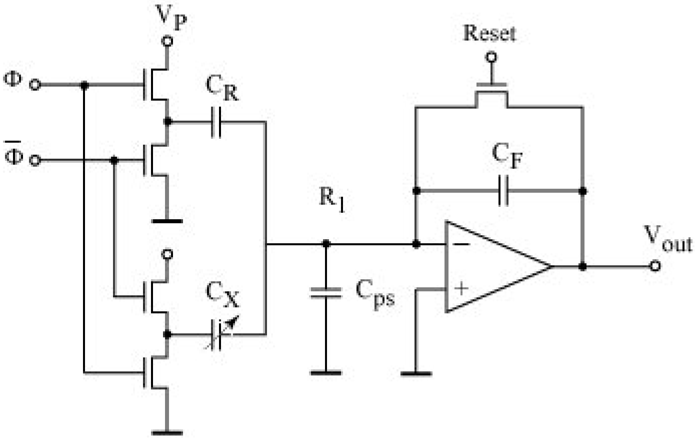

Figure 3.9 Capacitor charge to voltage converter using switched capacitor circuit.

A reset pulse initially nulls the output. Subsequently, when the clock switches, a charge proportional to the clock amplitude and the difference between the reference and variable capacitor is forced into the feedback capacitor C_F, producing an output voltage given by:

$$V_{out} = V_P \frac{C_X - C_R}{C_F} \tag{4}$$

Since this scheme measures the difference between two capacitors, it is unaffected by parasitic capacitance values that are common to both.

3.3 Capacitive Pressure Sensor Characteristics

The capacitive sensing scheme circumvents some of the limitations of piezoresistive sensing. For example, as the resistors do not have to be fabricated on the membrane, scaling down the device dimensions is easier because concerns about stress averaging and resistor tolerance are eliminated. For the capacitive pressure sensor, there are no mechanical contact error, friction error or hysteresis errors in the measurement. This type of sensor is highly stable and reproducible. It has minimum dependence on the temperature because the dielectric constant changes little with temperature. MEMS technology enables to manufacture signal conditioning circuits, needed to make the measurement, on the same wafer, very close to the sensor. Thus the interference of a stray capacitance can be reduced to a minimum and the sensor still has a very small size.

The advantages of capacitive sensors compared to piezoresistive devices are perceived as:

- High temperature operation (>125 °C)
- Virtually no power consumption
- High overpressure capability and high resistance to pressure shocks
- Low temperature coefficient

However, capacitive sensing presents other limitations. The capacitance changes nonlinearly with diaphragm displacement and applied pressure. The output impedance of the device is large, which also affects the interface circuit design, and the parasitic capacitance between the interface circuit and the device output can have a significant negative impact on the readout, which means that the circuit must be placed in close proximity to the device in a hybrid or monolithic implementation. An additional concern is related to lead transfer and packaging. In the case of absolute pressure sensors, the cavity beneath the diaphragm must be sealed in vacuum. Transferring the signal at the counter electrode out of the cavity in a manner that retains the hermetic seal can present a substantial manufacturing challenge.

3.4 Related Reading

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