AN ULTRA-SENSITIVE CAPACITIVE PRESSURE SENSOR WITH A BOSSED DIELECTRIC DIAPHRAGM

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ABSTRACT

This paper reports the development of an ultra-sensitive pressure sensor for a very small (<5cc) portable microinstrumentation cluster for environmental monitoring and process control. The device utilizes a thin stress-compensated dielectric diaphragm with a silicon boss. For a device with a 2.0mm-diameter 0.3μm-thick diaphragm and a 1.2mm-diameter 3.0μm-thick boss, the measured pressure sensitivity is more than 10,000ppm/Pa (5fF/mTorr), at least five times greater than other recent devices. The minimum resolvable pressure is 0.1mTorr, while the temperature coefficients of the zero-pressure offset and the pressure sensitivity are 910ppm/°C and -2900ppm/°C, respectively. These temperature coefficients can be reduced to 15ppm/°C and -63ppm/°C using digital compensation implemented through a six-term polynomial.

INTRODUCTION

As micromachining and wafer processing technology have improved, it has become possible to fabricate silicon pressure sensors with steadily-improving sensitivities. Such devices are needed for a broad variety of applications, including microphones for use in hearing aids [1-3], manometers for tracking barometric pressure variations, and instruments for use in automated process control [4]. Some of these applications require the sensors to be physically very small, to respond to very low differential pressures, and yet to operate over a considerable dynamic range. To satisfy these sometimes conflicting requirements, the research reported here has explored the use of a capacitive pressure sensor having an ultra-thin diaphragm and a center boss which serves as the conducting plate. The resulting devices have achieved pressure sensitivities as high as 5fF/mTorr, at least five times higher than other recent devices [1,4]. This paper describes the design approach used and discusses in detail the effects of such factors as diaphragm internal stress, device geometry, ambient temperature, and long-term operating drift. Digital compensation techniques are used for reducing temperature effects, and the present pressure resolution is compared to fundamental noise limits.

DESIGN AND FABRICATION

To achieve high sensitivity and wide operating range in a micromachined capacitive pressure sensor, one possible design approach is to use an ultra-thin diaphragm with a center boss. This approach has several advantages: 1) An ultra-thin diaphragm offers very high sensitivity; 2) A center boss enlarges the operating range and yields improved linearity; and 3) A nearly parallel-plate capacitor is obtained using the center boss. It is difficult, however, to analyze and optimize this structure. Earlier work [5] has expressed the center deflection of a circular diaphragm having a center boss as:

$$y = A_p\left(\frac{Pa^4}{Eh^3}\right) \qquad (1)$$

$$A_p = \frac{3(1-\nu^2)}{16}\left(1 - \frac{b^4}{a^4} - 4\frac{b^2}{a^2}\log\frac{a}{b}\right) \qquad (2)$$

where y is the center deflection, P is the applied pressure, E is Young's modulus for the diaphragm material, and a and h are the radius and the thickness of the diaphragm, respectively. A_p is a stiffness coefficient which is a function of the so called "solidity ratio of boss and diaphragm radii" (b/a). In (2), ν is Poisson's ratio and b is the boss radius. These two equations, however, assume that the diaphragm deflects linearly with applied pressure. In addition, they do not account for effects due to a finite diaphragm boss thickness and internal stress.

To accurately predict the device performance so an optimum design could be achieved with respect to both high sensitivity and dynamic range, an approach based on the finite-element method (FEM) was adopted in this work. An FEM software tool, CAEMEMS-D [6], was used to search for the best combination of the center boss dimension and the diaphragm thickness. The analysis has led to the following findings: 1) The linearity of the load-deflection characteristic improves as the boss thickness increases. This improvement is minor when the boss thickness is less than five times the diaphragm thickness but becomes significant when the boss thickness is about ten times the diaphragm thickness because with that thickness ratio, the center boss can, like a plate, deflect uniformly under load. 2) There is a trade-off in selecting the best solidity ratio (b/a) because it affects both the operating range and the pressure sensitivity. The center boss is designed to serve as a conducting plate for the capacitive pressure sensor; hence, when it is too small, a smaller than desired output signal (ΔC) results. On the other hand, too high a solidity ratio can make the diaphragm too stiff, degrading the sensitivity. After many design-simulation iterations, a near-optimum design was obtained which achieves high sensitivity, appropriate diaphragm rigidity, and a large output signal. In this design, the device has a gap of 2.76μm. The diaphragm is circular, 2mm in diameter, and 0.3μm in thickness. The center boss is also circular with a 1.2mm-diameter and a thickness of 3μm.

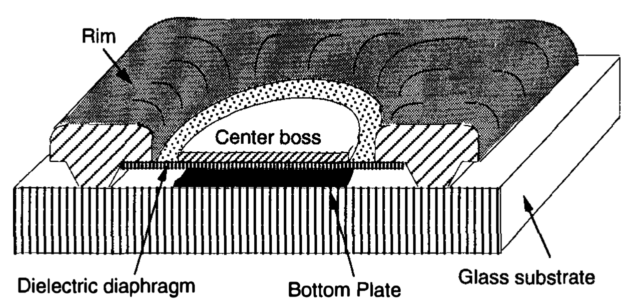

Fig. 1: A three-dimensional view of the ultra-sensitive capacitive pressure sensor

Figure 1 provides a three dimensional view of the capacitive pressure sensor. The device is composed of a glass base with patterned metal electrodes and an ultra-thin diaphragm with a center boss. The device is fabricated using a six-mask silicon bulk-micromachined dissolved-wafer process. The rim of the device is first defined using a deep boron diffusion, after which the recess defining the capacitor gap is formed by dry etching. The center boss is formed using a shallow boron diffusion, and the dielectrics which form the diaphragm are deposited by LPCVD (Si_3N_4-SiO_2-Si_3N_4, 600Å/1800Å/600Å) and patterned using dry etching. The wafer is then metallized to connect the center boss to the chip rim, inverted, and anodically bonded to the metallized glass plate. The device is then completed using an unmasked etch in EDP to remove the portions of the silicon wafer that are not etch-stopped. The top view of an actual device is shown in Fig. 2.

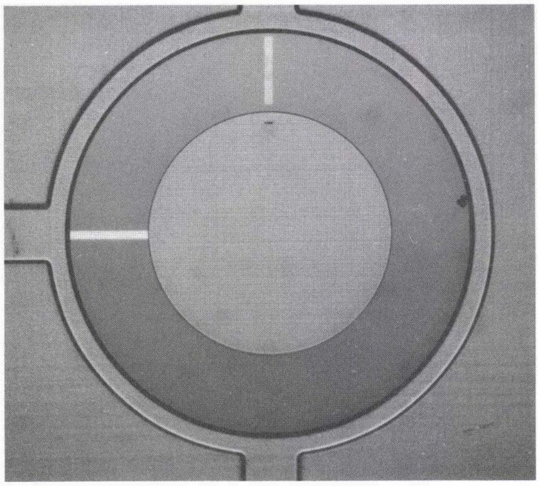

Fig. 2: Top view of a device having a 2mm diaphragm diameter

DEVICE PERFORMANCE

Device Linearity and Pressure Sensitivity

This ultra-sensitive capacitive pressure sensor design has been extensively tested. Figure 3 shows the measured capacitance change versus applied pressure. As can be seen, the capacitance change is highly linear because of the design of the center boss. Since the boss is ten times as thick as the diaphragm, most of the diaphragm deformation comes from stretching and bending of the dielectric layer. The minimum measured pressure sensitivity of the device is 5fF/mTorr, and the equivalent boss deflection is 25Å/mTorr. The minimum resolvable pressure is 0.1mTorr. The operating range of the device has been studied from 0 to 1000mTorr (0 - 130 Pa), which covers the range of sound pressure levels [7] and complements existing barometric devices.

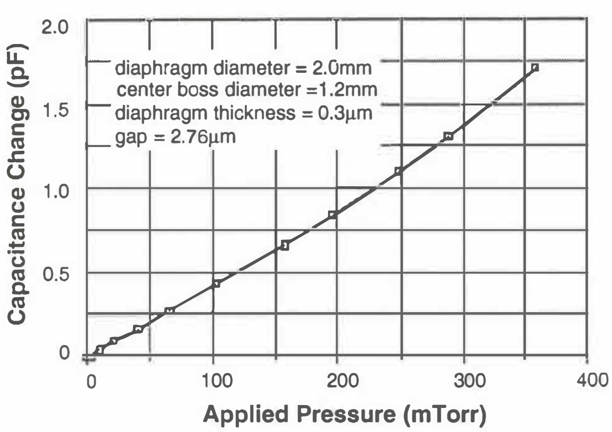

Fig. 3: Capacitance change versus applied pressure for a pressure sensor with a 2mm-diameter circular diaphragm

Diaphragm Internal Stress and Pressure Sensitivity

To investigate the effect of diaphragm internal stress on pressure sensitivity for an ultra-thin diaphragm with a center boss, the device has been compared with another fabricated device in which the diaphragm was formed using a two-dielectric sandwich of Si_3N_4-SiO_2 (2100Å/900Å). As an approximation, the average internal stress for the composite diaphragm structure is given by [8]:

$$\sigma_{avg} = \frac{\sigma_1 h_1 + \sigma_2 h_2}{h_1 + h_2} \qquad (3)$$

where $\sigma 1$ is the internal stress for Si_3N_4, $\sigma 2$ is the internal stress for SiO_2, and h_1 and h_2 are the corresponding layer thicknesses.

The calculated internal stress of the diaphragm for the ultra-sensitive device is only 60MPa, a stress level compatible with that for boron-doped silicon (40MPa), whereas the internal stress of the second diaphragm is 575MPa, about ten times higher. Figure 4 shows the measured capacitance change as a function of applied pressure for these two devices. As can be seen, the pressure sensitivity is 5fF/mTorr for the ultra-sensitive device and only 0.33fF/mTorr for the second device. The gap difference accounts for about a factor of two in this sensitivity reduction, while the increased diaphragm internal stress is responsible for a factor of more than seven.

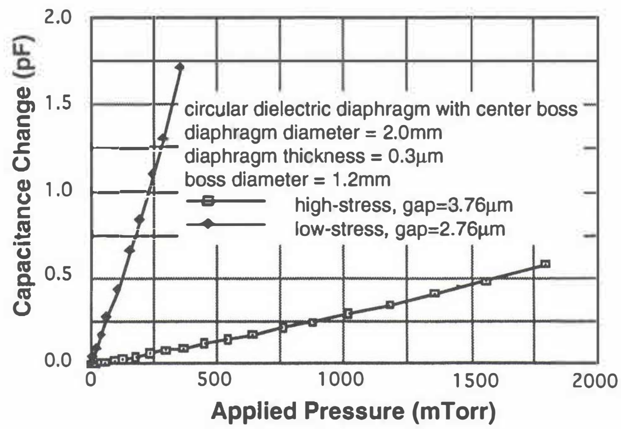

Fig. 4: Capacitance change vs. applied pressure for two capacitive pressure sensors with different diaphragm internal stress

Another important observation is that the device with a Si_3N_4-SiO_2 diaphragm structure also exhibited a large zero-pressure offset. A possible explanation is that when SiO_2 is deposited on top of the Si_3N_4 layer, the internal stress gradient in the thickness direction in the composite diaphragm will change from tensile on the top to compressive on the bottom (near the glass). When the diaphragm is released from its silicon substrate, a deformed diaphragm results due to this stress distribution in the diaphragm thickness direction, leading to a large zero-pressure offset. On the other hand, the zero-pressure offset observed for the ultra-sensitive device using the balanced Si_3N_4-SiO_2-Si_3N_4 diaphragm has been negligible.

Device Geometry and Pressure Sensitivity

For a device with a given diaphragm thickness and internal stress level, the size of the diaphragm and the capacitive gap distance become the main factors affecting the pressure sensitivity. To investigate these effects, the ultra-sensitive device was compared with a similar device which differs only in its diaphragm and boss diameters (1.5mm and 0.9mm). The measured pressure sensitivity is 5fF/mTorr for the ultra-sensitive device and 1.83fF/mTorr for the smaller diaphragm, reflecting a 63.4% loss for a 0.5mm reduction in the diaphragm diameter. This sensitivity loss is less than 83.5% calculated using Eqs. (1) and (2) in which the diaphragm internal stress and the boss thickness are ignored.

To study the effect of device gap changes on the pressure sensitivity, the ultra-sensitive device and a similar device with a larger gap (4.76μm) were compared. The minimum pressure sensitivity measured is only 1.25fF/mTorr for the second device. The pressure sensitivity therefore drops by 75% when the gap is increased by 2μm. According to the pressure sensitivity definition:

$$S_{cap} = \frac{1}{C_0}\frac{\Delta C}{\Delta P} \qquad (4)$$

where ΔC and ΔP are the changes in capacitance and pressure, and C_0 is the zero-pressure capacitance. The calculated pressure sensitivity drop here is 69.9% as the gap changes from 2.76μm to 4.76μm. The experiment results are thus in good agreement with the theory. To achieve very high sensitivity, the gap should be designed to be as small as possible, consistent with dynamic range requirements.

Temperature and Pressure Sensitivity

The pressure sensitivity and accuracy of a capacitive pressure sensor can easily be degraded due to operating temperature changes which are often not controllable. To study these temperature effects, a representative device was tested from 25°C to 100°C. Figure 5 illustrates the capacitance change as a function of applied pressure for different temperatures. An increase in temperature causes the response to decrease, probably due to the increasing diaphragm internal tensile stress as well as the thermal expansion of the glass base. According to [9], the thermal expansion coefficients for SiO_2, Si_3N_4, and glass are 0.5×10^{-6}/°C, 2.8×10^{-6}/°C, and 3.2×10^{-6}/°C, respectively. Since Si_3N_4 possesses a tensile stress on silicon and SiO_2 is compressive, the larger thermal expansion coefficient in Si_3N_4 results in a larger tensile stress in the diaphragm as temperature increases. Similarly, because the silicon rim is anchored to the glass base, the larger thermal expansion coefficient in the glass base induces additional tensile stress onto the diaphragm. Although these temperature effects are undesirable, the responses are repeatable; hence, they can be minimized using digital compensation techniques [10].

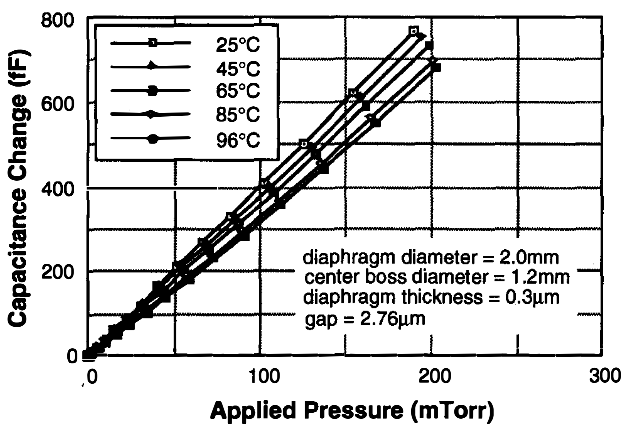

Fig. 5: Capacitance change versus applied pressure for a 2mm-diameter diaphragm at temperatures from 25°C to 100°C.

Long-Term Stability

The nature of its application as a precision measurement device requires that an ultra-sensitive pressure sensor be stable during its operating lifetime, meaning that its response surface does not move beyond a given tolerance range. In order to evaluate the stability of the fabricated sensor, a long-term test has been conducted on a representative device. In the test, a periodic square pulse (voltage) was applied to the diaphragm to induce deflection electrostatically. The pulses were equivalent to an applied pressure of 200mTorr. Alternating positive and negative square pulses were used so that any charge built up in the device during charging and discharging could be eliminated. The device was tested continuously for 1.93 million pulse cycles at a frequency of 1.49Hz. The capacitance versus applied pressure response was examined before and after the test; no noticeable change was found in the device response surface (zero-pressure offset or sensitivity). Any changes were less than the 0.05mTorr resolution imposed by the measurements, indicating that the dielectric diaphragms are mechanically stable, at least when operated over a limited pressure range (0-1000mTorr).

DIGITAL COMPENSATION

As discussed earlier, the capacitance response of the sensor is affected by temperature. Such an effect constitutes a shift in the response surface. Since the device is very sensitive and is designed for use over a low range of pressures, even a small amount of offset or drift in the response surface can be very detrimental to its performance. To correct the device response for temperature variations, digital compensation techniques have been used with this sensor. As a first step, the device was fully tested over a pressure range of 0-500mTorr and over a temperature range from 25°C to 100°C using a total of 80 test points. The measurement data were then analyzed using a statistical software package, RS/1, and were fitted with a quadratic model using multiple variable regression. Through analysis, the device compensation model was generated as a function of both the applied pressure and temperature:

$$C_{reg}(P,T) = 3.537068 + 0.004158P + 0.003795T - 0.000010P\cdot T + 9.542191\times10^{-7}P^2 - 0.000004T^2 \qquad (5)$$

where C_{reg} (in pF) is the predicted capacitance from this model, P (in mTorr) is the applied pressure, and T (in °C) is the external temperature. Figure 6 is a plot of the uncompensated response surface for the device with respect to both applied pressure and temperature. The device was digitally compensated, reducing the temperature coefficient of sensitivity from -2900ppm/°C to -63ppm/°C (0.05mTorr) over all the measurement points. The temperature coefficient of zero-pressure offset was reduced from 910ppm/°C to 15ppm/°C.

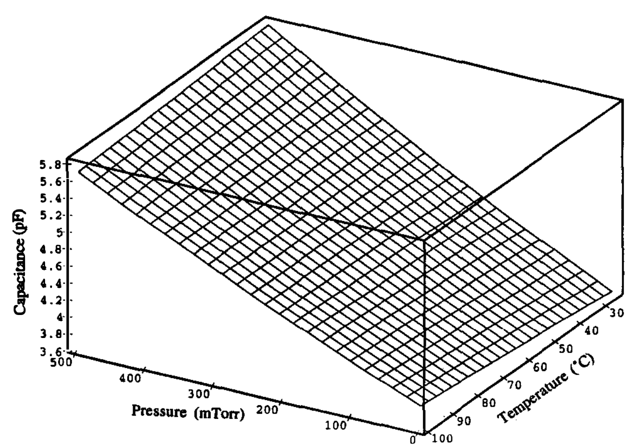

Fig. 6: Response surface of the ultra-sensitive pressure sensor

NOISE ESTIMATION

When developing an ultra-sensitive pressure sensor, the effects of noise should be estimated as a measure of how much further it is feasible to consider pushing the response of such a device. In our study, three important types of noise have been considered: Brownian noise, kT/C noise, and noise induced by voltage source (readout) variations. Brownian noise is mechanical-thermal noise resulting from the thermal agitation of molecules bombarding the diaphragm. The diaphragms of ultra-sensitive capacitive pressure sensors are especially susceptible to this type of noise. Since this molecular agitation of the medium surrounding the diaphragm creates local variations in pressure, it determines the minimum pressure resolution possible for a given measurement. The two-side power spectral density of the pressure fluctuation in the medium due to the thermal noise is defined as [11-13]:

$$\frac{S_p(f)}{\delta f} = \frac{2\pi k T \rho f^2}{c} \qquad (6)$$

where f is the frequency, k is the Boltzmann's constant, T is the absolute temperature, and ρ and c are the density and the speed of sound in the medium. As can be seen, the power spectral density of the pressure fluctuation is strongly frequency-dependent. It has been calculated that the root-mean-square thermal-noise pressure in air at room temperature and ambient pressure over the audio-frequency band (20-20KHz) is only $4.2\times10^{-3}\mu$Torr. Therefore, this noise can be neglected for low frequency applications.

The second type of thermal noise arises from the thermal agitation of the free electrons in an electrical conductor. For a capacitive pressure sensor, the spectral density of the thermal-noise voltage appearing across the sensor is given by [14]:

$$\frac{v_t^2}{\delta f} = \frac{4kTR}{1 + (\omega C R)^2} \qquad (7)$$

where k and T have the same definition as above, R is the resistance, ω is the angular frequency, and C is the capacitance from the sensor. The total mean-square noise voltage across the device throughout the complete frequency spectrum is kT/C. It can be calculated that the root-mean-square thermal-noise voltage at room temperature is 0.034mV, which reflects a pressure fluctuation of 0.001mTorr. This noise therefore does not limit the performance of the device studied here since it is two orders of magnitude lower than the minimum device resolution.

The third noise source arises from the bias voltage applied to the pressure sensor during readout. The resulting electrostatic pressure acting on the diaphragm during readout is a function of this bias voltage. It is estimated that the fluctuations in this bias voltage can be controlled to well below 1mV. If the bias voltage fluctuates ±1mV, the induced worst case equivalent fluctuation in pressure for the device would be 0.025mTorr. This type of noise therefore dominates all other noise sources for the present device.

CONCLUSIONS

The performance and the characteristics of an ultra-sensitive pressure sensor have been presented and discussed. The device exhibits a highly linear pressure-capacitance response. The measured pressure sensitivity is 5fF/mTorr. The sensor can resolve minimum input pressures as low as 0.1mTorr and can be used in very low pressure applications (0 to 1000mTorr). The temperature coefficient of sensitivity of this ultra-sensitive device can be digitally compensated to -63ppm/°C. Long-term tests show no noticeable change in the device characteristics after 1.9 million 200mTorr cycles at room temperature.

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