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Touch mode capacitive pressure sensors

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Abstract

Touch mode capacitive pressure sensors offer better performance in industrial applications than other devices. In touch mode operation, the diaphragm of the capacitive pressure sensor touches the substrate structure in operation range. The advantages of this mode of operation are near-linear output characteristics, large over-range pressure and robust structure that make it capable to withstand harsh industrial field environment. The principle, design, and characteristics of touch mode capacitive pressure sensors using various materials and technologies are discussed in this paper. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Capacitive sensor; Pressure sensor; Touch mode capacitive device; Capacitance to frequency converter; Si–Si capacitors

1. Introduction

Capacitive pressure sensor is known to have no turn-on temperature drift, high sensitivity and robust structure, and is less sensitive to side stress and other environmental effects. However its output is nonlinear with respect to input changes and the sensitivity in the near-linear region is not high enough to ignore many stray capacitance effects. In the normal mode operation, the diaphragm is kept at a distance away from the substrate as shown in Fig. 1a. If the sensor is designed to operate in the pressure range where the diaphragm is allowed to contact the substrate with a thin layer of insulator (t_m), as shown in Fig. 1b, then the device is a touch mode capacitive sensor [1]. In the operation range of touch mode capacitive pressure sensors, the diaphragm is designed to have a limited deflection range by a physical constraint to limit the deflection in the loading direction. The major component of output capacitance is the capacitance of the touched area with a thin layer of isolation layer which gives a larger capacitance per unit area compared to the air-gap capacitance in the untouched area. The touch mode device was developed to withstand harsh industrial environment, and with one or two orders of magnitude higher sensitivity than the normal mode operation in the near-linear operation range, so that some of the stray capacity effects can be neglected. This paper presents the principle, design and characteristics of touch mode capacitive pressure sensors. Other materials besides silicon may be used to fabricate touch mode sensors for various industrial applications using different manufacturing technologies. A summary discussion on various possibilities is included. The time-stable touch mode sensors can be embedded in industrial structures such as tires, stress elements; or packaged as sensors for field applications in industrial environments.

2. Principle

The basic element of a capacitive pressure sensor is an equivalent parallel plate capacitor with clamped edges, as shown in Fig. 1. The capacitance, neglecting the fringe effect, is expressed as:

$$C = \varepsilon \frac{A}{d}, \tag{1}$$

where ε is the permittivity of the media between the two plates, A is the area of the electrode plate, and d is the gap space between the two plates. The upper plate of the capacitor, known as the diaphragm, deforms when a differential pressure between the external environment and the inside chamber is applied. The general equation relating

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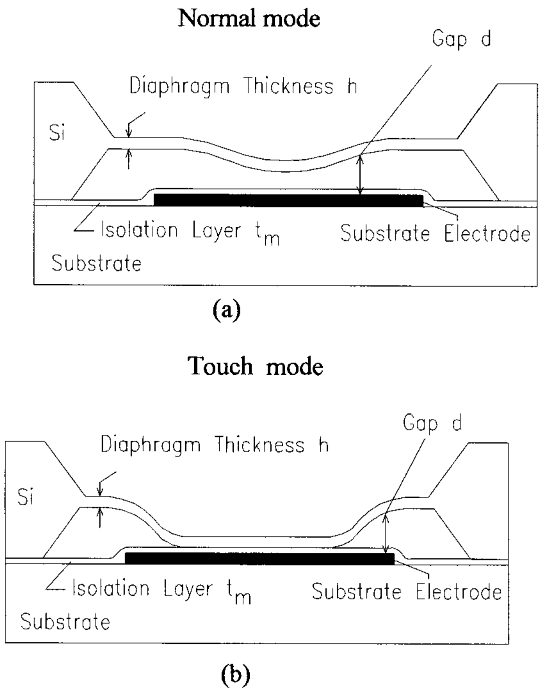

Fig. 1. Basic structure of a capacitive pressure sensor. (a) Normal mode, (b) touch mode.

the large deflection of a diaphragm, with residual stress, in normal operation region can be expressed as [2]:

$$\frac{\partial^4 F}{\partial x^4} + 2\frac{\partial^4 F}{\partial x^2 \partial y^2} + \frac{\partial^4 F}{\partial y^4} = E\left[\left(\frac{\partial w^2}{\partial x \partial y}\right)^2 - \frac{\partial^2 w}{\partial x}\frac{\partial^2 w}{\partial y}\right]$$

and

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial^4 y} = \frac{h}{D}\left[\frac{P}{h} + \frac{\partial F^2}{\partial y^2}\frac{\partial^2 w}{\partial x^2} + \frac{\partial F^2}{\partial x^2}\frac{\partial^2 w}{\partial y^2} - 2\frac{\partial^2 F}{\partial x \partial y}\frac{\partial^2 w}{\partial x \partial y}\right] \tag{2}$$

where D is the flexural rigidity, $D = Eh^3/[12(1-(\upsilon^2)]$; P is the differential pressure; w is the deflection at point (x, y); F is a stress function which is related to the deflection of the diaphragm; E is the Young's modulus; and υ is the Poisson's ratio.

In the normal operation mode of a capacitive pressure sensor, as shown in Fig. 1a, the diaphragm does not contact the substrate electrode. The output capacitance is nonlinear due to its inverse relationship with the gap ($d = d_o - w$, where d_o is the initial gap, w is the deflection), which is a function of pressure P, as given in Eq. (2). This nonlinearity becomes significant for large deflection regions. ($[w_o/h] > 0.3$, w_o is the center deflection). Many efforts have been made to reduce the nonlinear characteristics of capacitive sensors either by modifying the structure of sensors or by using special nonlinear converter circuits [3–8]. In the touch mode operation of a capacitive pressure sensor, the diaphragm is designed to work in the region where it touches the substrate mechanically, as shown in Fig. 1b. The major component of the sensor capacitance is that of the touched area where the effective gap is the thickness of the thin insulator layer, t_m, on the substrate electrode. Because of the small thickness and large dielectric constant of the isolation layer, t_m, the capacitance per unit area is much larger than that of the untouched area. The touched area can be expressed as $A_t = K_1 P - K_2 P^2$, where K_1 and K_2 are linear constant and saturation constant, respectively, and $K_1 \gg K_2$ [9]. Therefore, in a certain pressure range, the touched area is nearly proportional to the applied pressure, and results in the nearly linear C–P characteristics of the pressure sensor.

A typical C–P characteristic of a capacitive pressure sensor covering normal and touch mode regions is shown in Fig. 2. It has four regions, i.e., normal, transition, linear and saturation regions. The touch mode capacitive pressure sensors (TMCPS) operate in the region III—linear region. After the diaphragm touches the substrate, as discussed before, when the pressure increases further, the sensor capacitance is mainly determined by the capacitance of the touched area instead of the capacitance in the untouched 'normal operation portion area'. In region III of Fig. 2, the change of touched area is nearly proportional to pressure change, thus the C–P characteristics is nearly linear. In this touch mode operation region, the capacitance varies with pressure nearly linearly and the sensitivity (dC/dP) is much larger than that in the near linear region $(w_o/h < 0.1)$ of a normal mode device. In addition to the high sensitivity and good linearity, the substrate provides support to the diaphragm after touch, thus enables the device to have very large overload protection. In summary, the

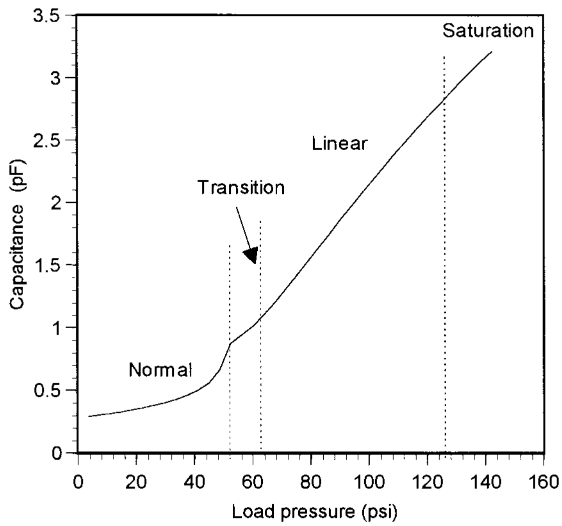

Fig. 2. A typical $C-P$ characteristic of a capacitive pressure sensor with four regions: normal, transition, linear (touch mode operation) and saturation regions. $a = 400$ μm, $h = 5$ μm, $g = 5$ μm.

advantages of TMCPS are nearly linear *C–P* characteristics, large overload protection, high sensitivity and simple robust structure that can withstand the industrial handling and harsh environment.

3. Design and fabrication of touch mode capacitive pressure sensors

Substrate and diaphragm are two basic components in the construction of a touch mode capacitive pressure sensor. The principle of touch mode capacitive pressure sensors can be applied to sensors with different diaphragm and substrate materials fabricated using different assembly techniques. The selection of size, diaphragm materials, and substrate materials depends upon application requirements, properties of available materials and fabrication process preferences. Examples of materials and techniques that can be used to assemble diaphragms and substrates to fabricate touch mode capacitive pressure sensors are listed in Table 1 [10].

The shape of diaphragms of TMCPS can be square, rectangular and circular. If the same active area is used, a circular diaphragm gives the largest sensitivity and the rectangular diaphragm gives the smallest sensitivity [11]. Since there is no sharp corner on the circular diaphragm, the maximum stress on the edges is reduced compared to the other two shapes. However, considering area efficiency (active area/dice area) and process capability using IC lithography, square and rectangular diaphragms are commonly used. A rectangular diaphragm with the length/width ratio greater than 3 can reduce the effect of the maximum stress near the corners on the sensor performance and the stress/deflection analysis can be closely approximated by one dimensional calculation [12].

Touch point pressure and the sensitivity in the operation range are the major specifications for the sensor. They are determined by material parameters, such as Young's modulus and Poisson's ratio, and sensor structural parameters including diaphragm thickness, size and shape of the diaphragm, gap distance between the two electrodes and thickness of the bottom electrode isolation layer. Untouched diaphragm behaviors, such as deflection and stress vs. pressure, can be determined analytically. The relationships of normalized pressure $[Pa^4/eh^4]$ normalized center deflection $[W_o/h]$ and normalized maximum stress $[\sigma_m a^2/Eh^2]$ are shown in Fig. 3 [12]. Touch point pressure is defined as the pressure load on the diaphragm when the diaphragm starts to touch the substrate. For diaphragms with clamped edges, the maximum deflection occurs at the center point of the diaphragm. By equating the center deflection of the diaphragm to the initial gap of the device, the touch point pressure can be calculated for a set of structural and material parameters of a sensor (or it can be estimated from Fig. 3). The center deflection, w_o, of a

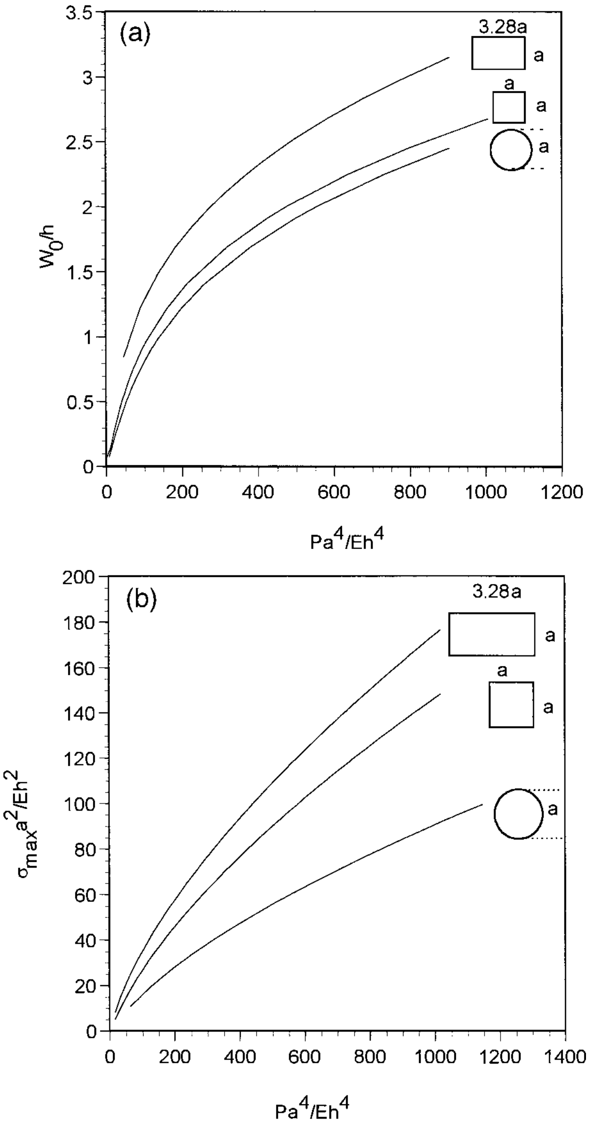

Fig. 3. (a) Dimensionless center deflection vs. dimensionless pressure of different shapes of diaphragms with constant width. (b) Dimensionless maximum stress of diaphragm with different shapes.

Table 1
Examples of touch mode sensors using various materials and technologies

Diaphragm material	Substrate material	Assembly technology
Single crystal silicon	Glass	Anodic bonding
Single crystal silicon	Silicon	Fusion bonding,
Poly-silicon	Silicon	Surface-micromachining
Silicon nitride	Silicon	Surface-micromachining
Polymeric materials	Silicon	Surface-micromachining
Metal	Glass/Ceramic	Eutectic bonding, soldering
Metal	Polymer	Polymeric seals
Ceramic (metallized)	Ceramic	Glass seal, metal seal
Polymeric materials (metallized)	Polymers	Polymeric seals, glues

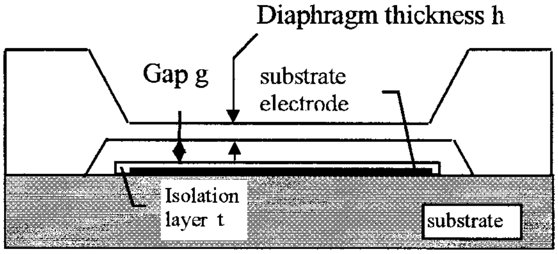

Fig. 4. Structure of a typical silicon–glass TMCPS.

diaphragm with clamped edges is given approximately in Ref. [2]. For circular diaphragms, the center deflection can be expressed as:

$$w_o = \frac{qr^4}{64D}\frac{1}{1+0.488\dfrac{w_o^2}{h^2}}, \quad (3)$$

where q is the pressure load, r is the radius, D is the flexural rigidity, and h is the thickness of the diaphragm. For square diaphragms, the center deflection can be expressed as:

$$w_o = 0.802\,a\sqrt[3]{\frac{qa}{Eh}}, \quad (4)$$

where a is half of the side length.

For rectangular diaphragms, there is no common equation to determine the center deflection because it depends on the ratio of the two side lengths, b/a. However, it can be determined by looking up the curves or tables from Ref. [2]. (For $b/a > 3.3$, the effect of b/a becomes negligible, the behavior of the diaphragm again can be determined.)

With a known diaphragm's center deflection at a desired touch point pressure, an initial gap can be designed to meet the specified start of the operation range. The sensitivity in the operation range is related to sensor's configuration and diaphragm's parameter [11]. In general, the lower the touch pint pressure, the larger the sensitivity. For the same touch point pressure, the sensitivity increases with decreasing of the diaphragm thickness. With the help of finite element analysis (FEA) or a CAD program designed according to FEA modeling results, the parameters of TMCPS can be designed to meet device performance specifications and fabrication constrains [11,13].

Three different constructions of touch mode capacitive pressure sensors have been successfully designed and fabricated. Fig. 4 shows a silicon–glass TMCPS using anodic bonding technique [14] to assemble the silicon diaphragm and a glass substrate with a metallized electrode. Fig. 5 shows a silicon–silicon TMCPS using silicon fusion bonding [11] to assemble silicon diaphragm and silicon substrate. Fig. 6 shows the polysilicon TMCPS using surface micromachining technology [15].

As an example, the fabrication of a silicon fusion bonded capacitive pressure sensor (SFBCPS) is described below. The structure of a SFBCPS is shown in Fig. 5. It consists of a deformable diaphragm with thickness h, an electrode on the substrate, referred to as the bottom electrode, and a vacuum reference cavity for absolute pressure measurement. The initial gap, g, between the diaphragm and the bottom electrode is defined by the depth of the cavity. The diaphragm of the sensor is formed by heavily boron-doped silicon (P^+) using dopant preference etching stop technique. The P^+ diaphragm is also used as one of the electrodes for the capacitive sensing. The annealing process for silicon fusion bonding limits the selection of the another electrode of the capacitive sensor. The electrode cannot use common metals, such as Al or Pt, as in Si–glass structure since the annealing temperature is normally higher than the eutectic temperature of most metals with the substrate material. Besides furnace contamination considerations, the metal can alloy with silicon at annealing temperature to cause high resistivity, open circuit and difficulty to wire bond problems in sensor packaging. Boron diffused layer on the N-type substrate is used as the bottom electrode with sufficiently low resistivity after the final anneals process. The P^+ electrode can also be easily wire-bonded even without metallization.

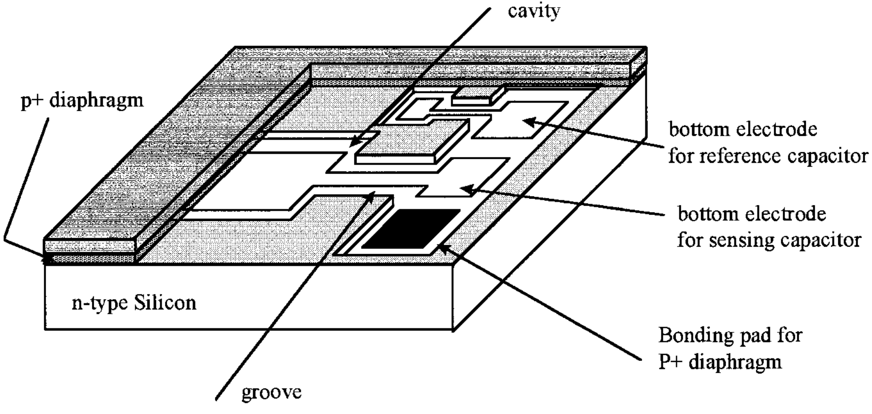

Fig. 5. Structure of a typical silicon fusion bonded capacitive pressure sensor.

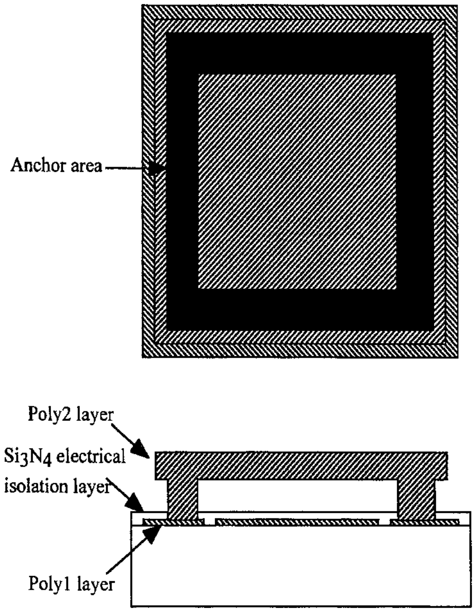

Fig. 6. Structure of a surface micromachined capacitive pressure sensor.

Heavily boron doped silicon (P^+) is commonly used as an etch-stop layer to make microstructures, such as diaphragms and beams. The dimension of the structures made from the P^+ layer can be precisely controlled. However, silicon fusion bonding of P^+ is difficult. Because the surface roughness of a P^+ layer is too large to achieve good bonding [16]. Fig. 7a shows an SEM picture of the silicon surface after 8-h boron diffusion. It can be noticed that there is a high density of pits (in addition to dislocation lines) on the surface. These pits will greatly reduce contact areas during initial contact in the silicon fusion bonding process, hence reducing the bonding force. A chemical mechanical polishing (CMP) process is developed to polish the silicon surface [17]. The slurry used is SCl by Cabot with an aggregate particle size of 100 nm and primary particle size of 30 nm. The wafer is undergoing both mechanical wearing and chemical etching simultaneously during polishing. The protrusions of different heights on the surface of the silicon wafer will experience different pressures and, subsequently, different wearing and etching. The difference in the remove rate will lead to smoothing of the surface. Fig. 7b is an SEM picture of the P^+ surface after 3-min polishing. Its micro-smoothness is compatible with the surface of a blank device-graded wafer. After CMP, the P^+ wafers become bondable.

Fig. 8 shows the outline of major steps of the fabrication of SFBCPS. Two silicon wafers are needed to make silicon fusion bonded capacitive pressure sensors. On wafer A, cavities are formed by silicon etching to define the gap. The bottom electrode on wafer A is formed by boron diffusion on the bottom of the cavity. A capacitive absolute pressure sensor needs an electrode feedthrough from a hermetically sealed cavity. In the design, the electrode feedthrough is laid down in a groove in the feedthrough region. (The groove is sealed after the bonding and etching processes.) The isolation between two electrodes of the sensor is realized by the thermal oxide on the bonding surface. Due to doping concentration-dependent oxidation, there is usually a step generated in the feedthrough region if the feedthrough electrode is on the surface. This will cause difficulties for silicon fusion bonding and hermetic sealing. The P^+ doped electrode laid down in a groove, on the other hand, will not disturb the silicon fusion bonding surface even with a thick oxide growth. An extra sealing process by LTO deposition (400 mTorr, 450°C) is used to get a hermetically sealed reference cavity of the sensor after diaphragm formation. The pressure inside the cavity is around 150 mTorr after the sealing process. On wafer B, heavily boron-doped diaphragm layer is formed by diffusion using solid source BN. After CMP, wafers A and B are bonded using Si fusion bonding, annealed at 1000°C for 1 h. P^+ etch-stop technique is then used to fabricate the diaphragm with the designed thickness.

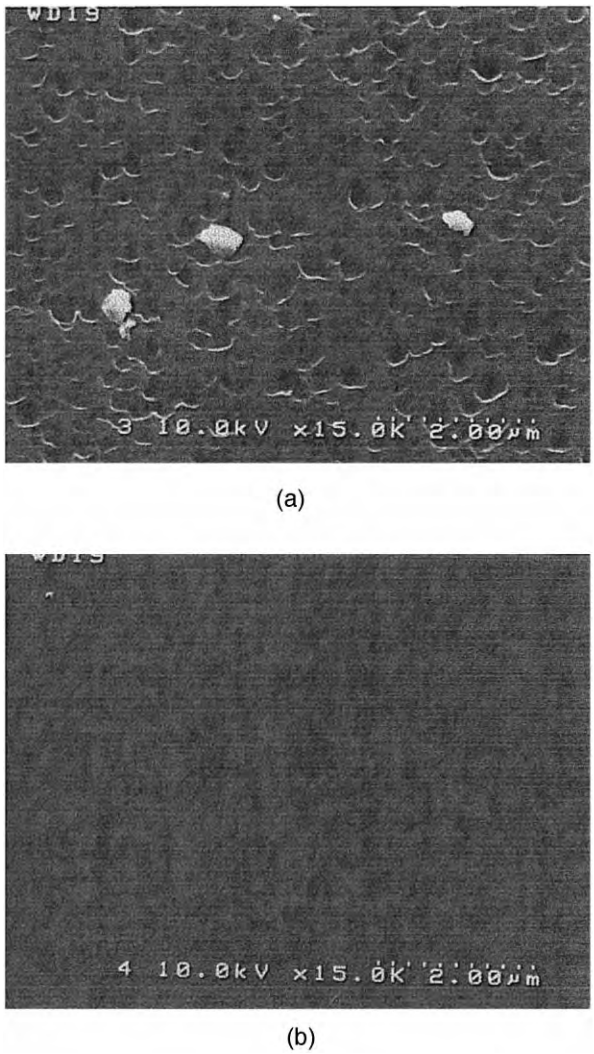

Fig. 7. SEM pictures of the P^+ silicon surface: (a) before and (b) after polishing.

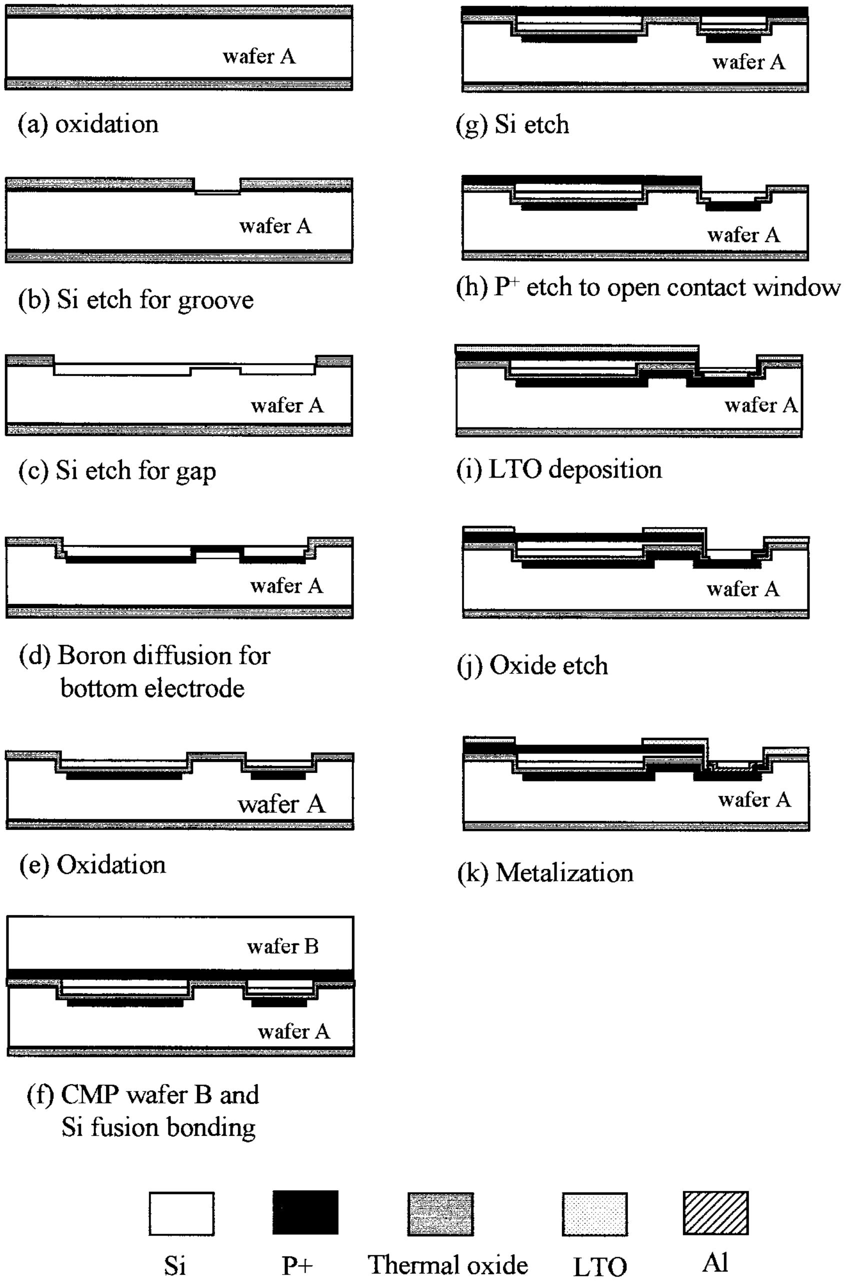

Fig. 8. Process outline of silicon fusion bonded capacitive pressure sensors.

A measured *C–P* characteristic of a touch mode SFBCPS is shown in Fig. 9. It clearly shows four operation regions, i.e., normal, transition, linear and saturation regions. The sensitivity measured in the range of 20 to 48 psi is 0.135 pF/psi. The nonlinearity measured is 0.68%. The sensitivity of the SFBCPS can be varied by adjusting process parameters without changing mask design. The device can be interfaced by CP-10 C/V and CP-11 circuit [11,18] to give a voltage output at about 0.05 to 0.1 v/psi in the operating range, or a frequency output at 3 kHz center frequency with a sensitivity of 100 Hz/psi.

The process discussed before can be simplified to a three-layer process. The structure of the fabricated sensor is illustrated in Fig. 10. The substrate as a whole will be used as the bottom electrode. The gap is defined by the thickness of thermally grown oxide. Since there is no electrode feedthrough required, the hermetically sealed reference cavity can be formed by silicon to silicon fusion bonding without introducing extra processes. There are two capacitors constructed on the sensor chip. One is constructed by silicon diaphragm and the substrate separated by a reference cavity plus the surrounding bonding area. This capacitor is pressure sensitive. The other is constructed by silicon diaphragm and the substrate separated by the oxide in the rest of the bonding area. It is insensitive to pressure and can be used as a reference

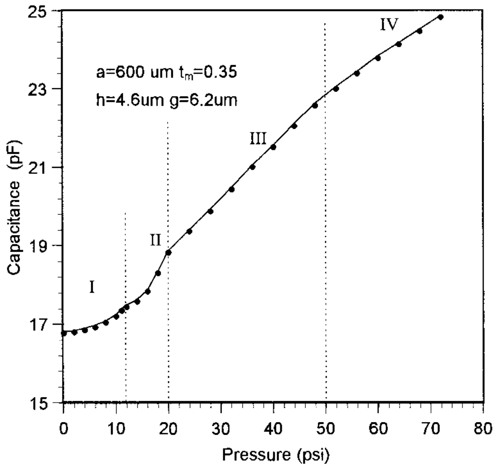

Fig. 9. A measured $C-P$ characteristic of a SFBCPS. I—normal region; II—transition region; III—linear region; IV—saturation region.

capacitor. The sensor chip is 1.0 mm × 1.5 mm × 0.4 mm in size. The diaphragm sizes range from 300 to 400 μm in diameter. The process starts with the P-type substrate silicon wafer with 2.2-μm thermally grown oxide. The thickness of the oxide determines the initial gap of the capacitive pressure sensor. The oxide in the cavity area is etched using RIE, which can give very vertical sidewall after etching. The same thickness of oxide on the backside wafer can be used not only as wet silicon etch mask, but also compensates the stress in the front side oxide so that the wafer can keep flat for the silicon fusion bonding. After cavity formation, a 0.1-μm-thick oxide is grown for the electrical isolation after the diaphragm touches the bottom. The top silicon wafer with a well-defined thickness of heavily doped boron is then bonded to the cavity patterned substrate wafer using silicon fusion bond technique. No alignment is required during the bonding. Following the bonding, the Si–Si 'wafer' is immersed in a dopant-dependent etchant (such as EDP, KOH and TMAH) to dissolve the silicon of the top wafer except the P^+ layer. The P^+ layer is then patterned to form the two capacitors and open the substrate contact window. Al contact pads are formed in the end using lift-off technique. This process utilizes single-side processing of silicon wafers. It only requires three noncritical masking steps and can produce very high yield.

Fig. 11 shows typical measured pressure characteristics of the sensor with a circular diaphragm. The linear operation range shown in the figure is from 30–70 psi. The sensitivity in the operation range is 0.086 pF/psi. It has been observed that one drawback of the silicon fusion bonded capacitive pressure sensors is that they have large zero-pressure capacitance, which limits applications of some capacitive interface circuits. The large zero-pressure capacitance originates from the large bonding area and the isolation material with large dielectric constant surrounding the diaphragm. At zero pressure, since the deflection of the diaphragm is small, the gap distance between diaphragm and the electrode on the bottom electrode is large. Therefore the capacitance of the air-gap capacitor contributes a small part to the overall capacitance at zero pressure. The zero-pressure capacitance is mainly determined by the bonding area required to ensure the hermetic seal and mechanically support of the diaphragm. In the current design, the measured zero-pressure capacitance of the fabricated sensor is 7.3 pF, of which the bonding area contributes about 80%.

CP10 and CP11, which are CMOS switched-capacitor C–V and C–F converters developed at Case Western Reserve University [11,18], can be used to overcome the

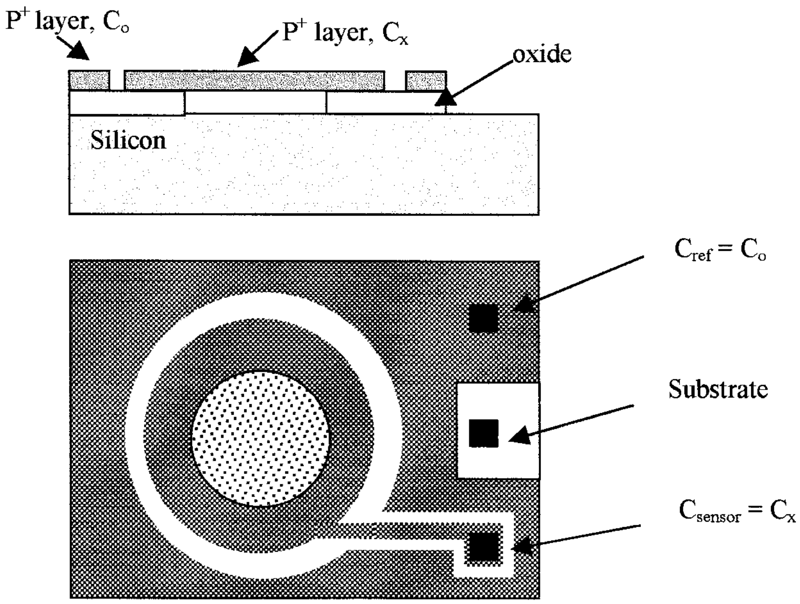

Fig. 10. Structure of a simplified silicon fusion bonded touch mode capacitive pressure sensor.

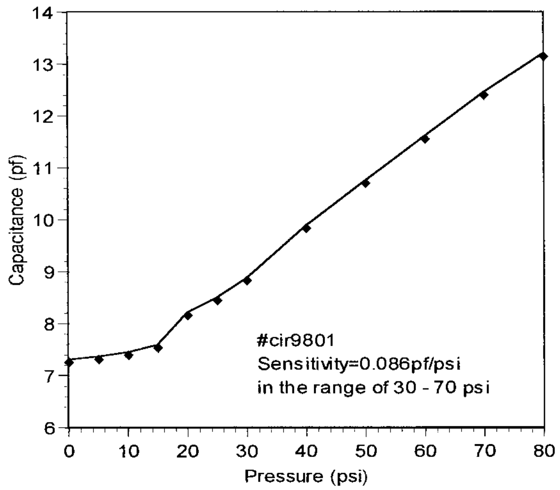

Fig. 11. Typical measured $C-P$ characteristics of simplified silicon fusion bonded touch mode capacitive pressure sensor.

obstacle for C/V or C/F converter due to the larger zero-pressure capacitance. Both converters have the ability to null out the zero pressure capacitance and to adjust the sensitivity and offset independently. The outputs of both converters are proportional to the charge difference between the measuring capacitor and a reference capacitor, which can be expressed as:

$$V = \frac{V_g C_x - V_o C_o}{C_f} \quad (5)$$

and

$$F = k(V_g C_x - V_o C_o), \quad (6)$$

where C_x and C_o are measuring capacitance and reference capacitor, respectively, and V_g and V_o are two DC voltages that can be used to control the gain, C_f is a constant capacitance, which can be used to adjust the circuit's sensitivity.

Fig. 12 shows the measured $C–V$ characteristics of the sensor shown in Fig. 11. The sensitivity in the operation range is 40 mV/psi where the capacitor C_f is 10 pF. It can be seen from Eq. (5), if smaller C_f is used, the larger voltage sensitivity can be obtained. The reference capacitor built-in the sensor structure can be used as a C_o in the CP-10 and CP-11 converter. Since it is fabricated and operated at the same condition as the sensing capacitor C_x, the built-in reference capacitor has the same temperature characteristics as the sensing capacitor. Fig. 13 shows the temperature characteristics of both the sensing capacitor C_x and the reference capacitor C_o of a silicon fusion bonded capacitive pressure sensor. This property is beneficial for the temperature characteristics of the sensor when it is used with a CP-10 converter. Using the built-in reference C_o instead of an external C_o, the temperature performance of the sensor with CP-10 converter has been improved from a relative error of $\pm 4.1\%$ to $\pm 0.66\%$ in the temperature range from 27°C to 100°C, as shown in Fig. 14.

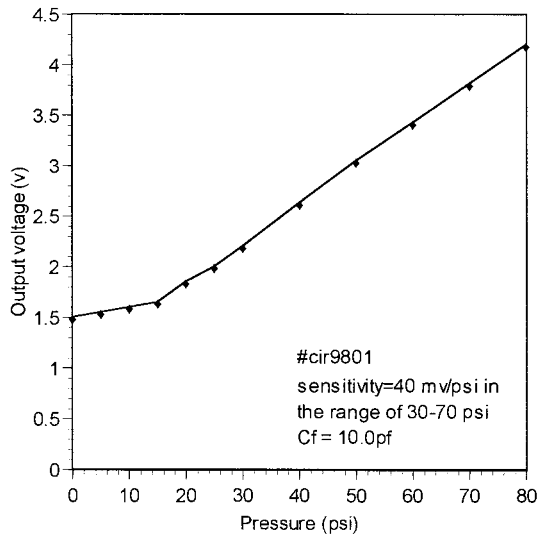

Fig. 12. Measured P–V characteristics of simplified silicon fusion bonded touch capacitive pressure sensor with CP-10 converter at 5 v simple power supply.

The touch mode capacitive pressure sensor has been designed and used for pressure monitoring embedded in tires as well as other field applications [19]. The sensors molded in tires have to survive high temperature, high pressure manufacturing processes, and to operate in harsh environment of repeated shock, vibration, stress, and temperature cycling for tens of years. It desires high sensitivity and good linearity to simplify the reading circuitry. The individual sensor chip is to be packaged on printed circuit board or ceramic substrate together with other instrumentation components of the system. Multiple layer package

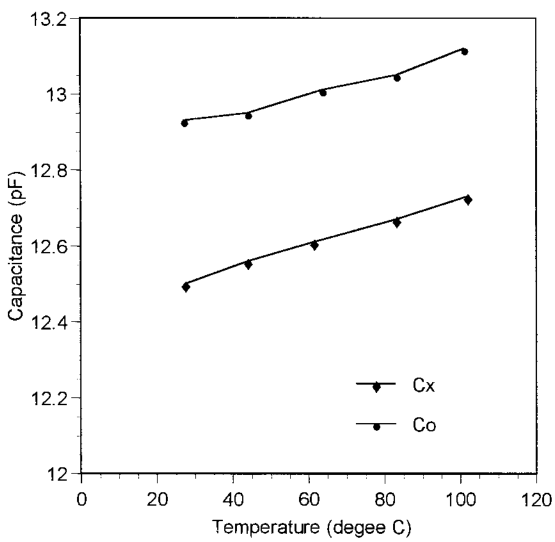

Fig. 13. Temperature characteristics of pressure sensing capacitor and built-in reference capacitor.

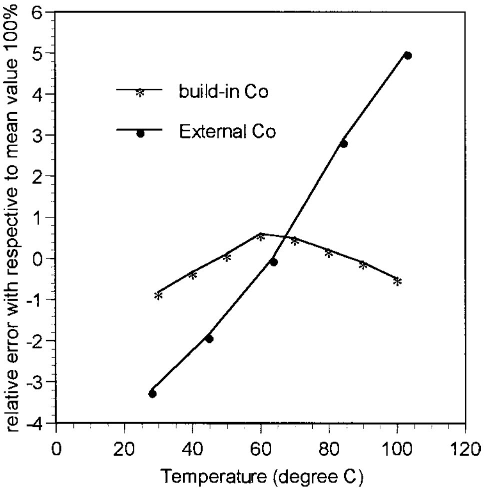

Fig. 14. Temperature characteristics of SFBCPS with CP-10 converter.

process was developed to protect the sensor from shock and interfering stress, and yet to transmit the pressure within the desired accuracy over the life of many decades [14]. It was molded at 300°C, at 400% overpressure for several hours and then evaluated in the field with no degradation in performance. Some sensors embedded in track tires under accelerated road tests for 5 months, 50,000 miles, showed no degradation of the pressure reading. Selected devices showed better than $\pm 5\%$ variation in system pressure readings in this period, including errors from sensors, signal processing circuits and telemetry subsystem.

4. Conclusion

The design, fabrication, and evaluation testing of touch mode capacitive pressure sensors for industrial applications are reported. The absolute pressure measuring device is demonstrated to have the advantages of good stability, low power consumption, robust structure, large overload ability and high $(\mathrm{d}C/\mathrm{d}P)$ sensitivity. The basic device design can be used to measure pressure from 10^{-4} to 10^{3} psi full scale with only changes of process parameters. It can withstand system-manufacturing temperature up to 300°C for several hours, and may have 200% to 200,000% full-scale over pressure protection. The experimental results show that the devices, especially used with built-in reference capacitor, have good temperature characteristics in the temperature range of 25°C to 100°C. This new mode of operation may supplement the piezoresistive and normal mode capacitive pressure sensors in industrial applications where mechanical and electrical stability are important. A CAD program was developed for the design of touch mode capacitive sensors [11,13]. With the program developed, sensors can be designed to meet given specifications and can also estimate the distributions of device performance from known variations of the process control.

With proper package, the fluid flow, force, acceleration and displacement can be converted into pressures. Therefore, the device can be used to measure flow, force, acceleration and displacement in automotive and other industrial applications. The design and simulation of silicon diaphragms would be applicable to diaphragms for other sensors, actuators, and microsystems such as fluid valves, pumps and switches.

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References

[1] X. Ding, L. Tong, W. He, J. Hsu, W.H. Ko, Touch mode silicon capacitive pressure sensors, Winter Annual Meeting of the American Society of Mechanical Engineers, Conference Dallas, TX, USA, Nov. 25–30, 1990, pp. 111–117.

[2] S. Timoschenko, Theory of Plates and Shells, McGraw-Hill, New York, 1940.

[3] J.H. Jerman, The fabrication and use of micromachined corrugated silicon diaphragm, Sensors and Actuators A21–23 (1990) 84–88.

[4] H. Sandmaier, Non-linear analytic modeling of bossed diaphragm for pressure sensors, Sensors and Actuators A25–27 (1991) 815–819.

[5] L. Rosengren, J. Soderkvist, L. Smith, Micromachined sensor structures with linear capacitive response, Sensors and Actuators A 31 (1992) 200–205.

[6] D. Crescini, V. Ferrari, D. Marioli, A. Taroni, Thick-film capacitive pressure sensor with improved linearity due to electrode-shaping, Measurement Science and Technology 8 (1) (1997) 71–77.

[7] T. Omi, K. Horibata, F. Sato, M. Takeuchi, Capacitive pressure sensor with center clamped diaphragm, IEICE Transactions on Electronics V E80 C (2) (1997) 263–268.

[8] K. Barun, E. Joseph, Linearization techniques for capacitive sensors, Micromachined Devices and Components, Austin, TX, 23–24 October 1995, pp. 206–214.

[9] X.X. Huang, Touch mode capacitive pressure sensor modeling, Master thesis, EEAP, Case Western Reserve University, Cleveland, OH, USA, May 1994.

[10] W.H. Ko, High sensitivity touch mode capacitive sensors, EDC/CWRU Report, May 1998.

[11] Q. Wang, Touch mode capacitive pressure sensor and interface circuit, PhD dissertation, Case Western Reserve University, Cleveland, OH, USA, Dec. 1997.

[12] M.D. Giovanni, Flat and Corrugated Diaphragm Design Handbook, Mercel Dekker, 1982.

[13] Q. Wang, W.H. Ko, Modeling of touch mode capacitive sensors and diaphragms, accepted for publication in Sensors and Actuators, 1999.

[14] W.H. Ko, Q. Wang, Y. Wang, Touch mode capacitive pressure sensors for industrial applications, Technical Digest Solid State Sensor and Actuator Workshop, Hilton Head Island, June 1996, pp. 244–248.

[15] X. Yang, Surface micromachined sensors and interface circuits, MS thesis, Case Western Reserve University, Cleveland, OH, USA, August 1997.

[16] M.A. Schmidt, Silicon wafer bonding for micromechanical devices,

Technical Digest Solid-state Sensor and Actuator Workshop, Hilton Head Island, SC, June 1994, pp. 127–130.
[17] A.A. Yasseen, Diffraction grating scanners using polysilicon micromotors, Master Thesis, EEAP, Case Western Reserve University, Cleveland, OH, USA, May 1996.
[18] W.H. Ko, G.J. Yeh, An integrated interface circuit for capacitive sensors, Microsystem Technologies 1 (1994) 42–47.
[19] W.H. Ko, Capacitive absolute pressure sensor for industrial applications, US patent, No. 5,528,452, June 1996.

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