TOUCH MODE CAPACITIVE PRESSURE SENSORS FOR INDUSTRIAL APPLICATIONS

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ABSTRACT

The principle, simulation, design, characteristics and application of touch mode capacitive pressure sensors are presented. In touch mode operation, the diaphragm of the capacitive pressure sensor is touching the substrate structure. The advantages of this mode of operation are: near linear output, large over-range pressure and robust structure that make it capable to withstand harsh industrial field environment.

INTRODUCTION

Capacitive pressure sensors are known to have no turn-on temperature drift, high sensitivity, robust structure and less sensitive to environment 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 of operation, the diaphragm is kept at a distance away from the substrate as shown in Fig. 1-a. 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. 1-b, then the device is a touch mode capacitive sensor. 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 near linear operation, so that some of the stray capacity effects can be neglected. This paper presents the principle, computer simulation, design, characteristics and application of touch mode capacitive pressure sensors.

PRINCIPLE

The basic element of a capacitive pressure sensor is an equivalent parallel plate capacitor with clamped edges, where the diaphragm would deform responding to a differential pressure applied to two sides of the diaphragm, as shown in Fig. 1. The capacitance, neglecting the fringe effect, is

$$C = \epsilon \frac{A}{d} \quad (1)$$

where ϵ is the permittivity of the media between the two plates; A is the area of the electrode plate; 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 the deflection of a rectangular diaphragm, without residual stress, in normal operation region can be expressed as:

$$D \left(\frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} \right) = P + N_x \frac{\partial^2 w}{\partial x^2} + N_y \frac{\partial^2 w}{\partial y^2} + 2N_{xy} \frac{\partial^2 w}{\partial x \partial y} - x \frac{\partial w}{\partial x} - y \frac{\partial w}{\partial y} \quad (2)$$

where D is flexural rigidity, $D = E/[12(1-\nu^2)]$; P is the differential pressure; w is deflection at point (x, y) ; N_x , N_y and N_{xy} are direct and shear stresses in a plane parallel to the plate surface; E is Young's modulus; and ν is Poisson's ratio.

In the normal operation mode of a capacitive sensor, the diaphragm does not contact the substrate electrode. The output capacitance is nonlinear due to its inverse relationship with the gap ($d_0 - w$, d_0 is initial gap), which is a function of pressure P , as given in equation (2). This nonlinearity becomes significant for large deflection, $[(w_0/h) > 0.3]$, w_0 is center deflection, and large sensing capacitance regions. Many efforts have been made to reduce the nonlinear characteristics of capacitive sensors either by modifying the structure of sensors or by using special non-linear converter circuits. In the touch mode capacitive sensor, as shown in Fig. 1-b, the major component of the sensor capacitance is that of the touched area where the effective gap is the small thickness of the thin insulator layer, t_m , on the substrate electrode. 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 of a normal mode device. 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. They were developed to meet the manufacturing and operational conditions of industrial applications. Its cross-section is shown in Fig. 1-b. After the diaphragm touches the substrate and as the pressure increases, the sensor capacitance is mainly determined by the capacitance of the touched area instead of the capacitance in the untouched "normal operation area". In region III, Fig. 2, the change of touched area is almost proportional to pressure, thus the C-P characteristics is nearly linear. The support of the substrate to the diaphragm after touch, enables the devices to have very large over-load protection. In summary, the advantages of TMCPs are: nearly linear C-P characteristics, large overload protection, high sensitivity and simple robust structure that can withstand industrial handling and environment.

COMPUTER SIMULATION — FINITE ELEMENT MODELING

It is important to have a good understanding of the deflection, stress and strain of the diaphragm in order to design capacitive pressure sensors properly. The output capacitance of a

capacitive pressure sensor can be calculated by integration over the deformed diaphragm with a series of equivalent parallel plate elementary capacitors where the effective gap is the difference between the zero pressure gap and the local deflection. In the normal mode, the deflection can be calculated from equation (2) by numerical approximation analysis [1, 2]. In the touch mode device, however, equation (2) is no longer valid. Hence the finite element modeling (FEM) of diaphragms is used to determine the touch mode deflection of the diaphragm. A uniform mesh of 24 x 18 elements, with 8 nodes for each element, in a quarter of the diaphragm is used as shown in Fig. 1-c. By geometrically nonlinear computing using ABAQUS, the deflection, stress and capacitance versus pressure at each node can be calculated for a set of sensor parameters a , b , h , and d , as shown in Fig. 1, and material properties E and ν . GAP element in ABAQUS is used to model the touch mode operation. Post data analyses based on information obtained on deflection at each node is developed to find the capacitance-pressure behaviors to predict the performance of simulated capacitive sensors [3].

From the FEM simulation, the performance of the capacitive sensor can be estimated as the device parameters are varied. The dimensionless deflection at the center point of diaphragms is shown in Fig. 3, where the normalized deflection ratio (w_0/h) is plotted against the normalized pressure (Pa^4/Eh^4) for two (b/a) ratios. The curves in Fig. 3 can be used to determine the touch point pressure (P_t) of known diaphragms by letting the center deflection equal to the initial gap (d_0). For a set of (a, b) and diaphragm material, the touch point can be selected by (h) and (d) using curves in Fig. 3. After touch, the stress in the touched area is tensile and the stress in the untouched area has three sub-regions as shown in Fig. 4. Fig. 5 shows the deflection along y-axis as the pressure is increased in equal steps. The deflection along x-axis has similar behavior. Beyond the touch point, the shape of the untouched portion of the diaphragm remains nearly the same. However, the touched area A equals to $(a + bP - cP^3)$ where a, b, c are constants [3], it increases nearly linearly at first, then approaches saturation for larger pressures. This explains the C-P characteristics in region III and IV in Fig. 2.

The average sensitivity (dC/dP) is defined as the slope of the straight line obtained by linear curve fitting over the working pressure range. The nonlinearity is defined as

$$\frac{|\Delta C_+| + |\Delta C_-|}{2(C_{\max} - C_{\min})} 100\% \quad (3)$$

where ΔC_+ and ΔC_- are the maximum and minimum deviation from a straight line characteristic, respectively; $C_{\max}$ and $C_{\min}$ are the maximum and minimum capacitance in the operation range, respectively.

It is found that the sensitivity is proportional to $(1/t_m)$. The sensitivity is also inversely proportional to the thickness of the diaphragm for a fixed touch point as shown in Fig. 6. Fig. 7 shows (dC/dP) sensitivity and nonlinearity versus touch point pressure.

These simulation results can predict the trend of the sensor's performance when the device parameters are varied. The understanding and quantitative curves can be used as a design tool to arrive at a specific desired performance. The results of the diaphragm deflection and stress in both touched and untouched regions are useful for micro-actuators incorporating diaphragms.

FABRICATION AND PACKAGE

For molded in-package pressure monitoring used in industries, the sensors 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 TMCPS was developed to meet these requirements. A rectangular diaphragm was selected to reduce the effect of the maximum stress near the corners on the sensor performance. With the help of finite element modeling, the parameters of TMCPS can be designed to meet device performance specifications and fabrication constraints. A flow chart indicating major fabrication process steps for the sensor chips is given in table 1. An isolation layer, t_m , is deposited over the substrate electrode to provide isolation in touched range and to aid the anodic bonding of silicon to the glass substrate to form a hermetically sealed cavity for absolute pressure measurement. This layer plays an important role in the TMCPS. Sputtered #7740 Pyrex glass is used as the insulating layer. The substrate material could be glass or silicon. A special process was developed to fabricate hermetic electrical feed-throughs to connect the electrodes inside the hermetically sealed cavity to external bonding pads. With carefully selected thickness of the isolation layer, #7740 glass substrate with thin sputtered glass can be anodically bonded to the silicon to achieve hermetical sealing [4].

The individual sensor chip is to be packaged on printed circuit board or ceramic substrate together with other components of the system. Multiple layer package 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. The resulting package is shown in Fig. 8. It was molded at 300°C, 400% overpressure for several hours and then evaluated in the field with no degradation in performance [4,5].

EXPERIMENTAL RESULTS

Hundreds of TMCPS, with device parameters and material properties given in Table 2, have been fabricated in Electronics Design Center, CWRU, for laboratory and field tests in the last two years. A typical P-V characteristic is shown in Fig. 9. The CP-10 CMOS C-V converter circuit [6] is used in the sensor evaluation to convert capacitance into voltage. The measured non-linearity, as defined in equation (3), is 0.6% in the range of 80-110 PSI.

The hysteresis was found in some sensors. The hysteresis of sensors is defined as the difference between the outputs when the pressure is cycled upward and downward, which can be expressed as follows:

$$H = \frac{\max|V_F - V_B|}{V_{\max} - V_{\min}} 100\% \quad (4)$$

where V_F and V_B are sensor's outputs when the forward and backward pressure are applied, respectively.

The hysteresis of TMCPS is mainly due to the quality of the isolation layer. Since the diaphragm presses against this layer during the operation, non-elastic deformation of the sputtered glass layer results in the sensor hysteresis. However, after a few high pressure cycles (400% overpressure), the glass layer is stabilized hence the hysteresis is reduced significantly. Two

hysteresis curves of a typical sensor is shown in Fig. 10. After a few 400PSI pressure cycles, the hysteresis can hardly be observed.

The sensors have been successfully molded in the industrial packages and are undergoing simulated life tests in proving grounds. Fig. 11 shows a TMCPS P-V characteristic before and after molding process, which consists of 300°C and 400% of full scale overpressure for one to two hours [5].

CONCLUSION

The FEM and computer simulation, design, fabrication, evaluation and field testing of touch mode capacitive pressure sensors in 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 (dC/dP) sensitivity. The basic device design can be used to measure pressure from 10^{-4} to 10^3 PSI full scale with only changes of several process parameters. It can withstand manufacturing package temperature up to 300°C for several hours after packaging, and may have 200% to 200,000% full scale over pressure protection. This new mode of operation may supplement the piezoresistive and normal mode capacitive pressure sensor in industrial applications where mechanical and electrical stability are important.

The initial step in developing a CAD simulation program for capacitive pressure sensor has been made. The modeling of touch mode capacitive sensors (neglecting the build-in stresses of the diaphragm) was developed to obtain a set of data base for a family of sensors over a range of device parameters. From the data accumulated, the effects of device parameters on the device performance can be estimated. These results would be useful to capacitive sensor designers in estimating the performance of device before fabrication and also may serve as a guide for adjustment of parameters to arrive at a desired performance in mass production.

The design and simulation of the diaphragm would be applicable to diaphragms for other sensors, actuators, and microsystems. The understanding on the deflection and stress of a diaphragm under various loads, with small or large deflection, will be useful for diaphragm design to accurately predict the behavior of the element under normal or touch modes operation.

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Table 1. TMCPS Process Flow Chart

Step	Name	Description
Silicon Process		
1	Oxidation	Generate masking layers
2	Photolithography I	Define Gap area
3	RIE Silicon etch	Form gap
4	Boron diffusion	Define the thickness of diaphragm
5	Photolithography II	Define the etch back area
Substrate (glass) Process		
6	Electrode I	Form substrate electrode by sputtering Cr/Pt/Cr
7	Isolation	Sputter 7740 glass over the substrate electrode
8	Electrode II	Form contact pad for the diaphragm
9	Pad	open windows for wire bonding pads
Final Process		
10	Anodic bonding	Bond silicon wafer to the substrate wafer
11	Silicon etch	Form diaphragm
12	Dicing	Dicing sensor chip

Table 2. Touch Mode Capacitive Pressure Sensor Parameters

Parameter	Symbol	Value	Unit
Diaphragm Length	a	1500	μm
Diaphragm Width	b	457	μm
Diaphragm Thickness	h	5.0-8.0	μm
Gap	g	5.0-8.0	μm
Insulator Layer Thickness	t _m	0.01-3.0	μm
Young's Modulus of Si (P*)	E	1.3E+11	Pa
Poisson's Ratio	v	0.3

(a) Normal mode of operation

(b) Touch mode of operation

(c)

Figure 1. Typical capacitive pressure sensor, structure
a,b - dimension of the diaphragm; d - gap, h - thickness;

Figure 4. Stress versus coordinate L1 Touch point $P_t=60$ psi
a=457 μm b=1500 μm h=6.0 μm g=7.95 μm

Figure 2. Typical C-P Characteristics of a TMCPs
I normal region ; II transition region;
III linear region; IV Saturation region.

Figure 3. Dimensionless Center Point Deflection

Figure 5. Deflection with different pressures along coordinate L3
a=447 μm b=1500 μm gap=7.95 μm h=6.0 μm

Figure 6. Sensitivity and nonlinearity versus diaphragm thickness

Figure 7. Sensitivity and nonlinearity versus touch point P_t

Figure 8. Package of TMCPs for the industry application

Figure 9. Typical C-P characteristics of a TMCPs
I normal region II transition region
III Linear region IV saturation region

Figure 10 Hysteresis in the touch mode operation, region (a) - normal mode; region (b) - touch mode

Figure 11. Field test results of sensor #9210084 molded in an industrial package. Curve (b) includes some pressure attenuation due to overall package.