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Capacitive Absolute Pressure Sensor with Curved Bottom Electrode

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Summary

In this paper, we present a capacitive pressure sensor with curved bottom electrode and analyze the capacitance–pressure (*c–p*) characteristic of the sensor. Finite element analysis (FEA) is utilized to simulate the performance of the sensor by ANSYS software. The sensitivity and initial capacitance of the sensor are increased by curved bottom electrode. A curvature radius of the electrode is analytically calculated for the optimum sensitivity in the square diaphragm structure. The proposed sensors are fabricated and tested. The sensitivity and initial capacitance of the fabricated sensor are 1.78pF/kPa and 0.98pF in full pressure range (from 0kPa to 100kPa) and increased 3.96 and 1.9 times as much as typical one(with plane bottom electrode), respectively. In this way, the sensitivity and the initial capacitance of capacitive pressure sensor could be simply increased.

Keywords: capacitive pressure sensor, curved electrode, sensitivity, initial capacitance, curvature radius;

1. Introduction

Capacitive pressure sensors are widely used for different kinds of applications owing to high sensitivity, low turn–on temperature drift, low power consumption and robust structure and their characteristics are improved thanks to the micro–electromechanical systems (MEMS) technique.

Capacitive pressure sensors can be simply classified into non–touch mode and touch mode sensors according to operating mode.

Touch mode capacitive pressure sensor is well known to have good linearity and large overload protection as compared to the non–touch mode one, and *c–p* characteristic of the sensors with curved and patterned bottom electrode is investigated [1, 2].

Non–touch mode sensor is more suitable as absolute pressure sensor rather than touch mode one and several diaphragm and electrode structures are proposed to improve the performance of sensor.[3~9]

The theoretical and numerical analysis and simulation on the deflection of flexible diaphragm are presented in many studies.[10~12] The sensitivity is very important factor in sensors and it is also important to increase the initial capacitance to decrease the effect of parasitic capacitance in the capacitive sensors.

In this paper, we propose a vacuum–sealed capacitive pressure sensor which consists of flexible silicon diaphragm and curved bottom electrode, and analyze and simulate the performance of the sensor. Also the proposed capacitive pressure sensors are fabricated and tested.

2. Sensor Structure Design

2.1. Structure description

The cross section of the sensor is shown in Fig. 1. The sensor consists of clamped–edged flexible diaphragm, curved bottom electrode and vacuum –sealed cavity. The single crystal silicon diaphragm as sensing unit of the pressure sensor is formed and the thickness is precisely controlled by silicon etching including KOH etching and deep reactive ion etching (DRIE). The curved bottom electrode is formed by deposing aluminum film on the glass substrate via thermal evaporation and patterning. The glass substrate is curvedly grinded by ball grinder.

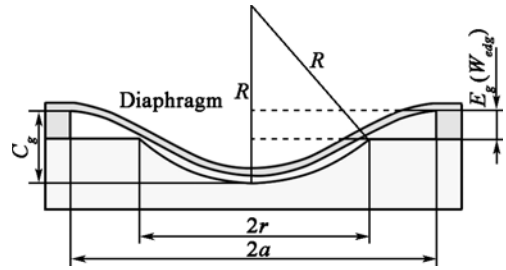

Figure 1. The cross section of the proposed sensor structure.

In Fig. 1, C_g is initial gap at the center of diaphragm, E_g is the initial gap at the edge of electrode, h is the thickness of diaphragm, a is a half width in the square diaphragm, r is radius of fixed bottom electrode, R is the curvature radius of electrode and w_{edg} is deflection of diaphragm at the edge of electrode.

2.2 Analysis and Simulation

In a square diaphragm, the small deflection at any point (x, y) can be determined by the following equation. [1, 2]

$$w(x,\ y) = \frac{p}{47D}\frac{(a^2-x^2)^2(a^2-y^2)^2}{a^4} \tag{1}$$

$$D = \frac{1}{12}\cdot\frac{Eh^3}{1-v^2} \tag{2}$$

In the above equations, p is applying pressure, E is the modulus of elasticity and v is Poisson ratio. And, the distance between diaphragm and curved bottom electrode at any point (x, y) can be calculated by Eq. (3) when the diaphragm is not deflected.

$$\Delta g(x,\ y) = R - \sqrt{R^2 - x^2 - y^2} \tag{3}$$

Therefore, the capacitance of the sensor under an applying pressure is calculated by the following equation.

$$C = \iint \frac{\varepsilon_0 \varepsilon dxdy}{g - \Delta g(x,\ y) - w(x,\ y)} \tag{4}$$

Fig. 2 shows the analytical and simulation results for performance of capacitive pressure sensors with curved and plane bottom electrodes. ANSYS software is utilized for simulation. In the model for simulation and analysis, half width in the square diaphragm (a) is 400μm, radius of fixed bottom electrode (r) is 300μm, thickness of diaphragm (h) is 10μm, initial gap at the center of diaphragm (Cg) is 5μm, modulus of elasticity (E) is 130GPa, and Poisson ratio (v) is 0.3.

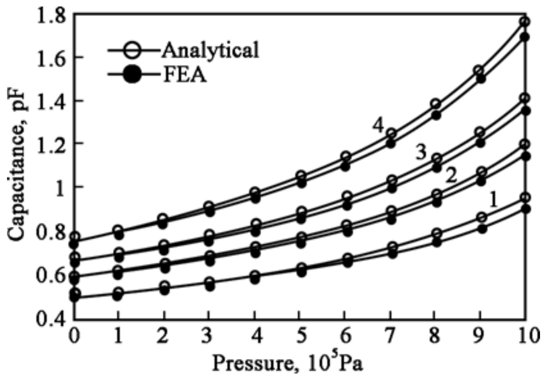

Figure 2. Analytical and simulation results of the proposed and typical sensors.

The pressure range is from 0kPa to 100kPa, curve 1 is the result of a typical sensor and curves 2, 3 and 4 are the results of sensors with curvature radius of 30, 20mm and 15mm, respectively.

As shown in Fig. 2, the sensitivities and initial capacitances of the sensors with curved electrode are increased to the typical one. Sensitivity and initial capacitance are increased by decrease of curvature radius of electrode and the optimum one can be analytically calculated.

From Fig.1, Eq. (5) is given by:

$$R - \sqrt{R^2 - r^2} = C_g - E_g \tag{5}$$

From Eq. (5), when the maximum deflection at the center of diaphragm is equal to C_g and E_g is equal to the deflection at the edge of electrode (w_{edg}), the optimum curvature radius (R_{opt}) can be calculated by the following equation:

$$R_{opt} = \frac{r^2 + (C_g - E_g)^2}{2(C_g - E_g)} = \frac{r^2 + \left(C_g - w\left(\frac{r}{\sqrt{2}},\ \frac{r}{\sqrt{2}}\right)\right)}{2\left(C_g - w\left(\frac{r}{\sqrt{2}},\ \frac{r}{\sqrt{2}}\right)\right)} \tag{6}$$

The optimum curvature radius is 11.2mm in the model, which is calculated by Eq. (6).

3. Fabrication and Experiment

The sensors are fabricated using the micro–fabrication technology. The main steps of the fabrication process are presented in Fig. 3.

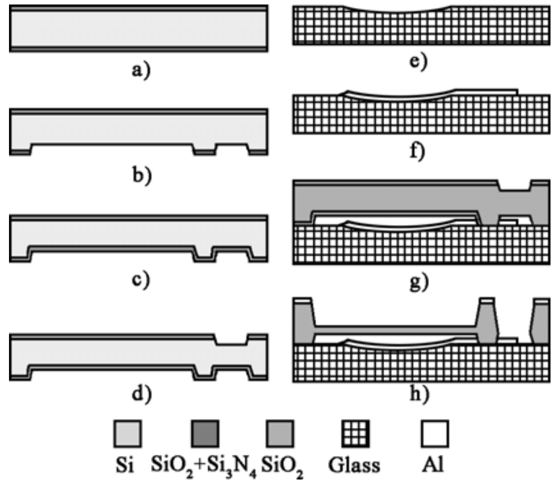

Figure 3. Fabrication process of the sensor

a) Thermal oxidation and LPCVD of Si_3N_4, b) Si etch for gap
c) Boron doping and formation of dielectric layer, d) Si etch for groove
e) Ball grinding for curved substrate, f) deposition and patterning of electrode, g) anodic bonding, h) Si etch for diaphragm

The fabrication starts with a double–side polished 3 inch n–type 100 silicon wafer, of which thickness is 250μm.

First, a 0.5μm dry thermal oxide is grown and low–pressure chemical–vapor deposition (LPCVD) Si_3N_4 with a thickness of 0.5μm is deposited on the wafer. Both the oxide and nitride layer serve as masks for the silicon etching including KOH etching and deep reactive ion etching (DRIE).

Next, the silicon wafer is etched from back side with KOH solution to form a gap (Eg) of 1μm.

Then, P^+ layer is formed by Boron doping and a 0.1μm dry thermal oxide is grown to form dielectric layer. After that, a groove of 10μm in depth is etched on the front side to prepare for the attachment of the electrode and also to decide the thickness of the diaphragm.

On the other hand, an aluminum film is deposited on the glass substrate grinded curvedly by ball grinder and electrode patterns, contact pads and leads are formed using lift–off technology.

In the next step, the silicon wafer and the glass substrate are bonded together by the anodic bonding technology. Then, bonded wafer is etched from top to form diaphragm, of which half width in 400μm. Finally the wafer is diced to each sensor.

Fig. 4 shows the c–p characteristic of the fabricated proposed sensor in comparison to the typical one.

The full pressure range is from 0kPa to 100kPa. The sensitivity and initial capacitance of the proposed sensor are 1.78pF/kPa and 0.98pF and increased as 3.96 and 1.9 times as the typical one, respectively.

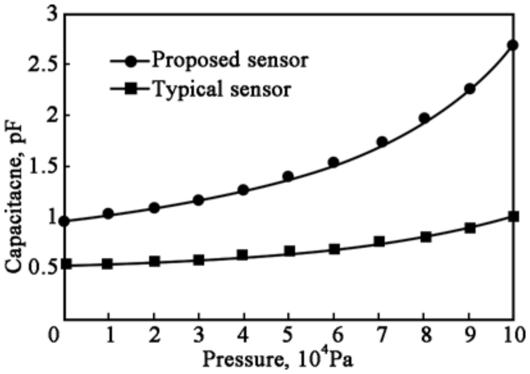

Figure 4. The experiment results of the fabricated sensors.
(1: Proposed sensor, 2: Typical sensor)

4. Conclusions

In this paper, we present a capacitive pressure sensor with curved bottom electrode. The analysis, FEA and experiment results show that the sensitivities and initial capacitances are increased by curved electrode in the sensors. The curvature radius of electrode is analytically calculated for optimum sensitivity. The proposed sensor is fabricated and tested in full pressure range from 0kPa to 100kPa. In the fabricated sensors, the sensitivity and initial capacitance of proposed one are 1.78pF/kPa and 0.98pF and increased as 3.96 and 1.9 times as the typical one, respectively. In this way, the sensitivity and the initial capacitance of capacitive pressure sensor could be simply increased without the increase of structure dimension size.

Acknowledgements

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