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An analytical thermal-structural model of a gas-sealed capacitive pressure sensor with a mechanical temperature compensation structure

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ABSTRACT

A coupled thermal-structural model of a gas-sealed capacitive pressure sensor is presented. The gas-sealed capacitive pressure sensor is used specifically for human activity monitoring, to measure atmospheric pressure in our research. A mechanical temperature compensation structure is utilized to reduce the thermal drift of the gas-sealed pressure sensor. In order to determine the compensation results of the temperature compensation structure, a thermal-structural model is presented. Classical laminated plate theory is used to derive the equations of equilibrium for clamped circular laminated plates containing one or more layers. Methods to estimate the model parameters and types of compensation structures are discussed, and model verification via experimentation is presented. The findings indicate that the resultant model is relevant, thus enabling the design of a mechanical compensation structure for a gas-sealed capacitive pressure sensor, to reduce thermal drift.

1. Introduction

Capacitive pressure sensors, as one of the most popular microelectromechanical systems (MEMS) sensors, have been widely used during the past 20 years [1,2]. Most of the capacitive pressure sensors use a diaphragm and a pressure cavity to create a variable capacitor, to detect strain due to applied pressure [3,4]. The diaphragm is exposed to the applied pressure on one side, and to a reference pressure on the other. Based on the reference pressure, the capacitive pressure sensors are classified as absolute pressure sensors, where the reference pressure is a vacuum [5,6]; and relative pressure sensors, where the reference is not a vacuum. If the applied pressure is close to the reference pressure, the capacitance change will be larger, and specifically the sensitivity will be larger. In our research, the pressure sensor is utilized for human activity monitoring [7] to measure atmospheric pressure. In order to obtain a higher sensitivity at the pressures typically found in human environs, around 1 atm, a gas-sealed pressure sensor is adopted and designed. However, a problem with the gas-sealed capacitive pressure sensor is the large thermal drift due to the thermal expansion of the gas inside of the cavity. Thus temperature compensation is necessary for gas-sealed capacitive pressure sensors. The conventional temperature compensation method uses a temperature compensation circuit to measure the temperature [8], which is electronically complicated and requires additional integrated electronics. In this paper, a mechanical temperature compensation method developed by the author [9,10] is used to reduce the thermal drift.

Analytical evaluation is one of the valuable processes used for pressure sensor design. There are various finite elements analysis (FEM) software and theoretical calculation models for simulations of vacuum-sealed pressure sensors. For example; a very low capacitive pressure sensor, based on the complementary metal-oxide semiconductor (CMOS) process, is simulated by CoventorWare software [11], Intellisuite software is used for modeling and simulating of MEMS capacitive pressure sensors [12], and Ansys software is used for simulating a silicon, directly bonded, capacitive absolute pressure sensor [13]. Whereas these software and calculation models are applicable to absolute pressure sensors, they are not applicable to gas-sealed pressure sensor designs. For gas sealed pressure sensors, the cavity pressure changes with temperature and diaphragm deformation. Therefore, an accurate modeling of gas-sealed pressure sensors performance with the above mentioned FEM software's can be considered very difficult, or even impossible. In our previous work [9,10] Ansys was used to simulate the thermal drift of the sensors. However, due to the complexity of the coupling simulations, the change in cavity pressure due to deformation was not taken into account, compromising the

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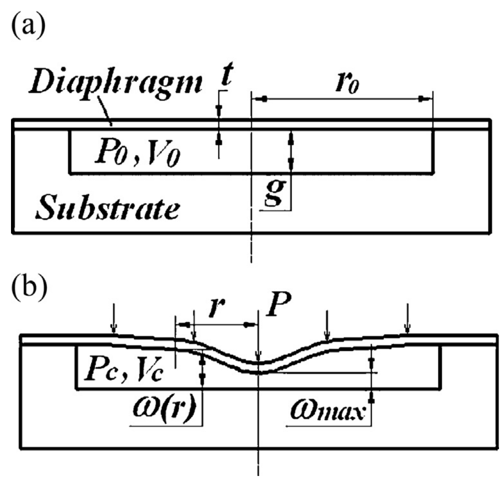

Fig. 1. Working principles of the gas-sealed pressure sensor: (a) when applied pressure is identical to initial cavity pressure and (b) when that applied pressure changes.

accuracy of the results. In this work, an analytical thermal-structural model of a gas-sealed pressure sensor with a circular diaphragm is presented as an effective solution for the accurate modeling of gas-sealed pressure sensors. Three different mechanical compensation structures are presented and the accuracy of the proposed analytical model is experimentally evaluated.

In this paper, we focused on the design of a gas-sealed capacitive pressure sensor, including a mechanical temperature compensation structure. We then fabricated gas-sealed capacitive pressure sensors, both with and without compensation structures, to verify the validity of the calculation model.

2. Gas-sealed pressure sensor design

2.1. A pressure sensor without a temperature compensation structure

The principle of the gas-sealed capacitive pressure sensor is illustrated in Fig. 1. The sensor cavity is sealed with nitrogen gas, with an initial pressure (P_0). When the ambient pressure (P) is identical to the initial pressure of the cavity, there will be no diaphragm deflection and no capacitance change, as shown in Fig. 1(a). When the ambient pressure changes, the diaphragm will bend up or down in response to the pressure difference between the ambient air and the sensor cavity air, which induces a capacitance change as shown in Fig. 1(b). In this case, the inner pressure of the cavity becomes P_c due to the volume change of the cavity.

A circular crystal silicon diaphragm with a radius of r and a thickness of t is a sensitive membrane. The gap of the cavity is g. The pressure–deformation relationship of the flexible silicon diaphragm can be derived from clamped plate theory [9,14].

The following expression for the deflection of the plate is obtained:

$$\omega(r) = \omega(0)\left[1 - \left(\frac{r}{r_0}\right)^2\right]^2 \tag{1}$$

where $\omega(0)$ is the center deflection of the plate, for a small deflection of the plate:

$$\omega_s(0) = \frac{Pr_0^4}{64D} \tag{2}$$

When the deflection has the same order of magnitude as the thickness of the plate, the internal membrane strain cannot be neglected.

Table 1
Material parameters for calculations.

Materials	E (GPa)	α (ppm/K)	ν
Si	170	2.6	0.28
Al	70	23.1	0.35

The large deflection of the plate is approximated via an energy-based analysis:

$$\omega_l(0) = \frac{Pr_0^4}{64D}\frac{1}{1 + 0.488(\omega_l(0)^2/t^2)} \tag{3}$$

D is the flexural rigidity, which is defined as:

$$D = \frac{Et^3}{12(1-\nu^2)} \tag{4}$$

If the downward deflection is assumed to be positive, and the upward deflection is assumed to be negative, then the capacitance between the diaphragm and the substrate is:

$$C_m = \int_0^{r_0} \frac{\varepsilon_0\varepsilon_r 2\pi r}{g - \omega(r)}dr \tag{5}$$

where E is Young's modulus of silicon, ν is Poisson's ratio, and r_0 is the radius of the diaphragm. ε_0 and ε_r are the permittivity of the vacuum and the relative dielectric constant of air, respectively.

According to the equation of state of ideal gas, if the temperature remains constant, the relationship between the initial pressure (P_0) and the pressure P_c of the cavity is given by:

$$P_0V_0 = P_cV_c \tag{6}$$

If the ambient pressure (P) remains constant, the temperature changes from initial temperature (T_0) to T, and the relationship between the initial pressure (P_0) and the pressure (P_c) of the cavity is given by:

$$\frac{P_0V_0}{T_0} = \frac{P_cV_c}{T} \tag{7}$$

The volume of the sealed cavity is calculated by:

$$V_0 = \int_0^{r_0} 2\pi r(g - \omega_0(r))dr \tag{8}$$

$$V_c = \int_0^{r_0} 2\pi r(g - \omega(r))dr \tag{9}$$

$w_0(r)$ is the diaphragm deflection at the initial state.

Comparing the small deflection and large deflection models, it is common practice to use a small deflection model if the membrane will deflect less than half of its thickness, otherwise a large deflection model would be more accurate. In our design, the thickness of the diaphragm and the pressure cavity gap are very close in magnitude, so the downward deflection will approximate the diaphragm thickness. Therefore, the large-deflection model will be utilized for the other calculations in this article.

The initial state assumes the cavity pressure is 100 kPa at 20 °C, and the diaphragm has no initial deflection. The material parameters used in the calculations were obtained from COMSOL's [15] material library and are listed in Table 1. For a pressure sensor with a silicon diaphragm with a radius of 1 mm and a thickness of 5 μm, the pressure characteristics and temperature characteristics are calculated with different cavity gaps, as shown in Figs. 2 and 3. When the temperature is 20 °C, the cavity capacitance and the cavity pressure both change with the applied pressures, as shown in Fig. 2(b) and (c), respectively. It is found that the narrower the cavity gap, the higher the sensitivity. The initial cavity volume is determined by the cavity gap, and when the applied