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MEMS pressure sensor based on optical Fabry–Perot interference

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ABSTRACT

In this paper, we present a microelectromechanical systems pressure sensor based on Fabry–Perot interference using anodic bonding, and the design principles and basic mechanical model are introduced. It is found that there is a difference between the experimental and theoretical deflections; thus, it is necessary to consider the actual structure. Furthermore, the sensor is fabricated using lithography, etching, and anodic bonding. Within the pressure measurement range of 0–0.1 MPa, the linearity is 99.996%, and the sensitivity is 74.6 nm MPa^{-1}. The test results indicate that the deflection is consistent with the theoretical analysis.

1. Introduction

Microelectromechanical systems (MEMS) pressure sensors are desirable in biomedical, environmental, and microsystem applications because of their advantages such as a small size, electromagnetic interference immunity, resistance to harsh environments, and multiplexing capability [1–5]. At present, pressure sensors are mainly based on Fabry–Perot (FP) interferometers, which consist of two partially reflecting parallel mirrors separated by a gap. With this robust structure, loaded pressures can be easily measured by detecting the changes in the reflected or transmitted optical signals due to the shift in this gap [6–9]. Among these sensors, a diaphragm structure is mostly employed, and anodic bonding technology is generally used for the assembly, such as those created by the anodic bonding of a silicon diaphragm onto a glass substrate with a previously etched cavity [10,11]. When analyzing the properties of a sensitive diaphragm, the typical ideal mechanical model is used, which does not take into account the actual anodic bonding process caused by the thermal stress and other factors. This analytical method will lead to a certain deviation between the experimental results and the theoretical design, which will cause difficulties in the sensor design.

In this paper, an optical FP pressure sensor using MEMS technology is proposed. The finite element software ANSYS is used to simulate the deflection of a silicon diaphragm under a thermal stress. The experimental results confirm the accuracy

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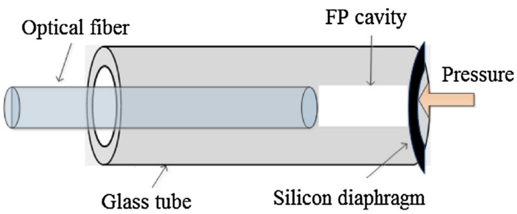

Fig. 1. Sketch of optical fiber pressure sensor.

Table 1
Material properties and geometric parameters of the proposed sensor.

Material	E (Pa)	μ	α (K^{-1})	d (mm)	h (μm)
Si	1.6×10^{11}	0.28	2.6×10^{-6}	1	100
Glass tube	6.275×10^{10}	0.2	3.2×10^{-6}	1	×

of the modified equation, which provides important theoretical guidance for the design and application of diaphragm-type pressure sensors.

2. Sensor design and fabrication

2.1. Basic mechanical model

The proposed MEMS pressure sensor is designed by following the principles of FP interferometers. Single-crystal silicon is designed as a sensor-sensitive diaphragm, which is connected to a Pyrex glass tube by using anodic bonding; then, an optical fiber is inserted into the glass tube and fixed by a glass adhesive. A schematic of the optical fiber pressure sensor is illustrated in Fig. 1. When the external pressure changes, the silicon diaphragm will deform by a certain amount, changing the length of the FP cavity correspondingly, which will cause a shift in the reflectivity spectrum of the FP interferometer. By measuring the reflection spectrum, the applied pressure can be obtained.

According to elastic mechanics, for a fixed ideal circular membrane and in the case of small deflection changes, the central deflection of the silicon film can be expressed as [12]

$$\omega_0 = \frac{3PR^4(1-\mu^2)}{16Eh^3}, \tag{1}$$

where P is the pressure, h is the thickness of the silicon diaphragm, R is the radius of the diaphragm, E is the Young's modulus, and μ is the Poisson's ratio.

Considering the actual experiment, the silicon diaphragm and glass tube are bonded at a high bonding temperature using anodic bonding, and the general bonding temperature is 350–400 °C. In this experiment, a bonding temperature of 377 °C is used because of the different thermal expansion coefficients of silicon and glass; when the sensor operating temperature and bonding temperature are different, a thermal stress σ on the bonding interface is produced, which can be expressed as [13,14]

$$\sigma = \frac{E_1E_2(\alpha_1-\alpha_2)\Delta T}{E_1(1+\mu_2)+E_2(1-\mu_1)}, \tag{2}$$

where E_1, μ_1, and α_1 denote the Young's modulus, Poisson's ratio, and coefficient of thermal expansion of the silicon film, respectively, and E_2, μ_2, and α_2 denote those of the glass tube, respectively, ΔT denotes the amount of temperature change. The specific material properties and geometric parameters are shown in Table 1.

Considering the bonding thermal stress of the diaphragm, the deflection of the diaphragm ω_0 can be corrected to

$$\omega_1 = \frac{PR^4}{64D + 4.36\sigma R^2}, \tag{3}$$

where $D = \frac{Eh^3}{12(1-\mu^2)}$ represents the bending stiffness of the diaphragm.

A numerical simulation of the proposed sensor was carried out using the finite element analysis software ANSYS to understand the actual deflection of the diaphragm after bonding with the glass tube for the applied pressures. The Solid 187 model was selected as the element type, and the material properties of the silicon diaphragm and glass tube were set. Then, the model was established, and meshing was performed. A pressure load of 10 kPa was applied, and the simulation was finally run. The ANSYS simulation process is illustrated in Fig. 2.

By ANSYS modeling and the simulations of different pressures P, the diaphragm deformations under different pressures were obtained, as summarized in Table 2.