The design and fabrication of an optical fiber MEMS pressure sensor

Ge Yixian,Wang Ming*, Rong Hua,Chen Xuxing

Jiangsu Key Lab of Opto-electronic Technology, School of Physical Science and Technology, Nanjing Normal University, 210097, Nanjing China
*corresponding author: wangming@njnu.edu.cn

ABSTRACT

A novel pressure sensor based on Fabry-Perot interferometry and micro-electromechanical system (MEMS) technology is proposed and demonstrated. Basic micro-electromechanical technique has been used to fabricate the pressure sensor. Fabrication process and packaging configuration are proposed. The loaded pressure is gauged by measuring the spectrum shift of the reflected optical signal. The experimental results show that high linear response in the range of 0.2-1.0 Mpa and a reasonable sensitivity of 10.07 nm/MPa (spectrum shift/pressure) have been obtained for this sensor.

Keywords: pressure sensor; MEMS; optical spectrum shift

1. INTRODUCTION

By employing the MEMS technology, a variety of optical MEMS pressure sensors based on Fabry-Perot interferometry have recently been proposed and fabricated[1-4], such as those using non-planar membrane to form the pressure-sensitive diaphragm[3], those involving bonding of a planar membrane onto the polished fiber end face or Pyrex glass[2] , those aligning two optical fibres whose ends are used to form the Fabry-Perot cavity[4] and so on. Optical MEMS sensors have additional advantages over traditional electrical sensors, including high adaptability in harsh environments, immunity to electromagnetic interference and the possibility of measurement for distributed physical quantities such as pressure, temperature and stress. They can be easily incorporated into sensor arrays by using multiplexing methods and are expected to be suitable for liquid and gas pressure measurement. But the high cost of manufacture instruments as well as the complicated process techniques is needed. To a certain extent, simplification of the sensing elements and fabrication process will be helpful for mass production and commercialization of this kind of pressure sensors.

Fundamental Problems of Optoelectronics and Microelectronics III
edited by Yuri N. Kulchin, Jinping Ou, Oleg B. Vitrik, Zhi Zhou
Proc. of SPIE Vol. 6595, 659541, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.726498

In this paper, we designed and fabricated a kind of optical MEMS pressure sensor which provides a wider measurement range, better linearity and sensitivity. The MEMS pressure sensor is fabricated by using basic and simple MEMS technique. Theoretical analysis of the design and the experimental results are presented.

2. THEORETICAL ANALYSIS

As shown in Fig. 1, the pressure-sensing element consists of a glass plate and a silicon diaphragm where a deep cavity is anisotropically etched into the upper surface and a shallow cylindrical cavity is etched into the underside surface. The incident light comes into the cavity through a single model fiber and is reflected by the silicon diaphragm. When pressure is loaded on the silicon diaphragm, the Fabry-Perot cavity length will change and that equal to the deflection of the silicon diaphragm. Since there exists a close relation between the depth of the air gap and the reflection spectrum, it is expected that one can easily know the loaded pressure by measuring the spectrum shifts.

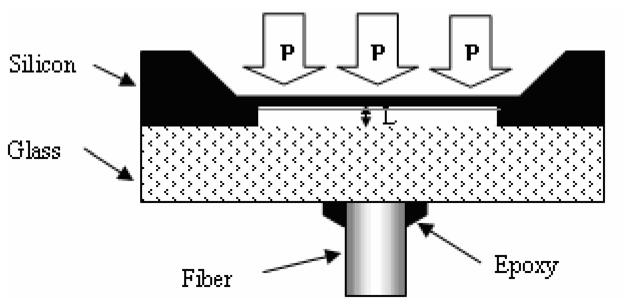

Fig.1 The sketch of optical fiber MEMS pressure sensor

As known from the principle of elasticity[5], the deflection ω(r) of diaphragm due to a loaded pressure p is given by

$$\omega_0 = \frac{3PR_0^{\ 4}(1-\upsilon^2)}{16Eh^3} \tag{1}$$

Where ω_0 is the deflection of the center position of diaphragm, R_0 is the radius of silicon diaphragm, E is the Young's modulus, υ is the Poisson's ratio, and h is the thickness of silicon diaphragm.

The sensor reflectance is given as

$$R(\lambda) = I_R / I_0 = \left| \frac{r_1 + r_{23}\exp(j\Omega_1)}{1 + r_1 r_{23}\exp(j\Omega_1)} \right|^2 \tag{2}$$

where r_{23} is the reflection coefficient of the composite structure which consists of a layer of air sandwiched between glass and aluminum and is given by

$$r_{23} = \frac{r_2 + r_3 \exp(j\Omega_2)}{1 + r_2 r_3 \exp(j\Omega_2)} \tag{3}$$

and

$$\Omega_1 = \frac{4\pi}{\lambda} n_{\text{glass}} t_{\text{glass}}, \quad \Omega_2 = \frac{4\pi}{\lambda} n_{\text{air}} t \tag{4}$$

where r_1, r_2 and r_3 are the reflection coefficients for normal incidence at the fiber-glass, glass-air and air- aluminum interface, respectively, and

$$r_1 = \frac{n_{\text{fiber}} - n_{\text{glass}}}{n_{\text{fiber}} + n_{\text{glass}}}, r_2 = \frac{n_{\text{glass}} - n_{\text{air}}}{n_{\text{air}} + n_{\text{glass}}}, r_3 = \frac{n_{\text{air}} - n_{\text{Al}}}{n_{\text{air}} + n_{\text{Al}}} \tag{5}$$

where λ is the operating wavelength, t_{glass} is the thickness of glass layer, and t is the air cavity depth.

According to the formulas presented, the relation between reflectivity of the sensor and wavelengths when air cavity is changed can be simulated. The parameters are as follows: the refractive index of optical fiber is 1.468; the thickness and refractive index of glass are 500μm and 1.473, respectively; because the refractive index of aluminum is much smaller than that of the air, the reflection coefficient of air-aluminum interface approximates 1, but considering the dissipation of light, we assume it is 0.5. The initial air cavity depth is 4.6μm.

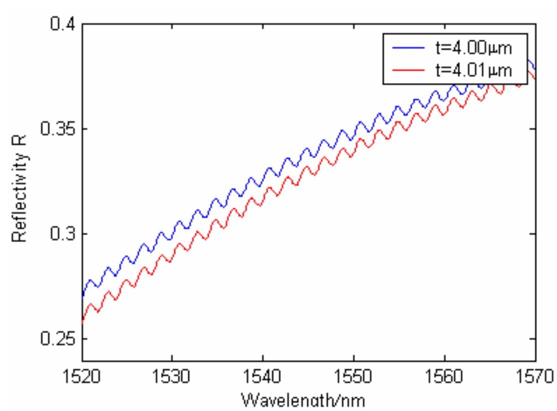

Figure2 Simulation of reflectivity when depth of cavity is 4.00 μm and 4.01 μm

3. FABRICATION OF THE SENSING ELEMENTS

Some surface and bulk MEMS processing techniques are used to fabricate the sensing elements on a 4-inch silicon wafer. The thickness of the silicon is 400μm and its orientation is p –type <100>. We start with making the thermal oxidation (SiO_2) and deposition of the silicon nitride (Si_3N_4) on the surface of the silicon wafer by using low pressure chemical vapor deposition (LPCVD).The silicon nitride will act as the mask in wet etching of the Si.

Reactive ion etching (RIE) is a widely-used technique for fabricating via holes in films. Etching can be attributed to two distinct mechanisms: chemical etching caused by the free

radicals and physical etching caused by ion bombardment[6].The RIE plasma is generated by the application of a RF power separated in a reactive, gaseous chemical mixture of electrons, ions, and free radicals which produce a distinctive glow. Some of these species combine with the substrate material and form volatile products that etch the wafer. Also the impinging ions can physically knock off surface atoms.In the experiment, SF_6 is used to etch SiO_2 and Si_3N_4,the flow of the gas is 40sccm.When etching the SiO_2 ,the gas pressure is 20 Pa and the RF power is 250W.The gas pressure is 5 Pa and the RF power is 300W when etching the Si_3N_4.The results show that it has a faster etching rate and a lower roughness.

Anodic bonding is now mostly used for silicion-glass bonding. The anodic bonding process is an electrochemical process. Cations within the glass, such as sodium ions, moves through the glass to the cathode forming a depletion layer close to the anode when adding voltage[7]. For silicon micromachining very often the glass plate consists of Pyrex glass.Due to the special composition of Pyrex glass the thermal mismatch between the glass and the silicion substrates has been minimized.Also it is rich in alkali ions.The surfaces of both bonding materials (silicion and glass plate) should be polished smoothly .In the experiment , Pyrex 7740# has been chosen and its thickness is 500μm.The voltage is about 800-1000V and the temperature is about 300-400℃.

Fig. 3 shows the processing steps. The process is initiated with the oxidation of the silicon wafer on both sides and deposition of the silicon nitride by using LPCVD (Figure3a). Then the reaction ion etching (RIE) and lithography technology are employed to remove the SiO_2 and Si_3N_4 ,and selectively open a window in the upper side which is protected by thick photoresist (Figure3b). RIE and lithography technology are also performed to obtain a shallow circular cavity (Figure3c) to form the Fabry-Perot interferometer. In order to make sure the accuracy of double-face alignment technology which is used to align the silicon wafer and glass wafer in anodic bonding process ,the shallow circular cavity and the open window are fabricated on the same silicon wafer. Then aluminum is sputtered on the etched part of the silicon with the thickness of 1000 Angstrom in order to enhance the reflectivity and prevent the light coming into the silicon (Figure3d). Fabricated wafer is anodically bonded onto the Pryrex7740# glass wafer (Figure3e). A potassium hydrate (KOH) anisotropic etching is performed to thin the silicon wafer down to the desired diaphragm thickness (Figure3f). The size of the open quadrate window is designed to be 2mm×2mm. A magnetic force stirrer is used to mix round the KOH solution and keep up the uniformity of silicon thickness.

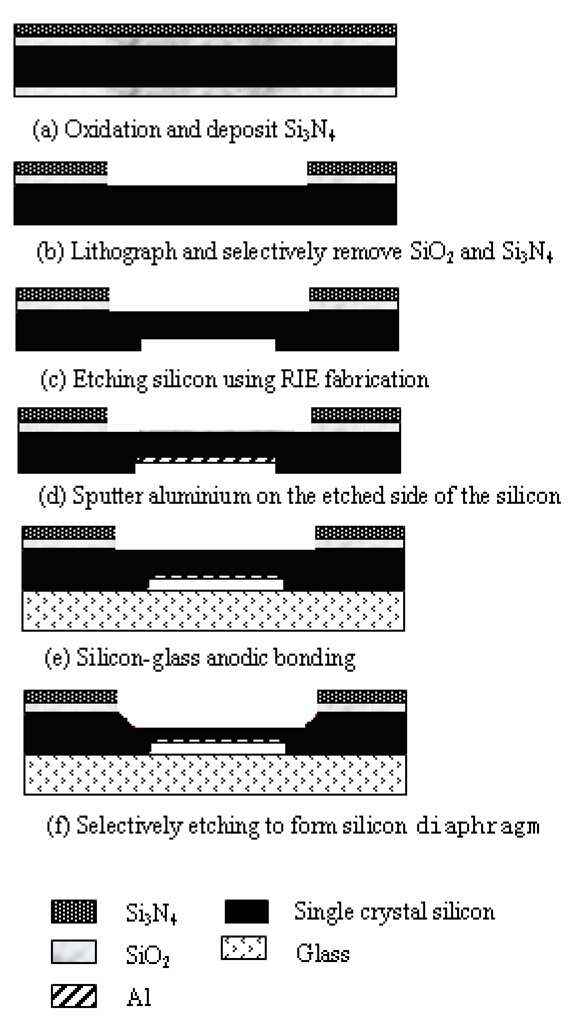

Fig.3 Fabrication process

Finally, the formed sensing arrays are cut into individual ones using a standard dicing saw. the fabricated structure and the fiber are packaged with epoxy method. Cavity depth between silicon diaphragm and the Pyrex glass is 4.6 μm. The thickness of the glass is 500 μm. The radius of the cavity is 600 μm and the diaphragm thickness is about 40 μm. The uniformity of the diaphragm thickness is less than 0.5%.

4. EXPERIMENT RESULTS

Pressure tests have been carried out by employing a set-up illustrated in Fig. 4. The system consists of a broadband amplified spontaneous emission (ASE) light source (OPLINK, USA), a 2×2 coupler, an optical spectrum analyzer (AQ6317C, Ando, Japan), single mode fibers and index matching liquid.

Besides, the pressure calibration was implemented by using a standard pressure meter with a pressure resolution of 0.02%.

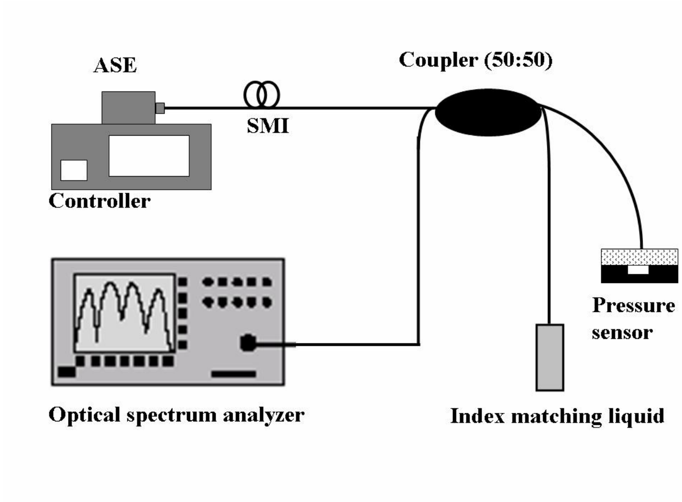

Fig.4 Experimental set-up for the optical MEMS Presure Sensor

Figure 5 shows the relation between the loaded pressure and the shifted wavelength. It is found that a good linearity with less than 0.27 nm standard deviations for the present sensor can be obtained. The sensitivity (i.e., changed wavelength /loaded pressure) and response range of this pressure sensor were estimated to be 10.07 nm/MPa and 0.2 Mpa to 1.0 MPa, respectively.

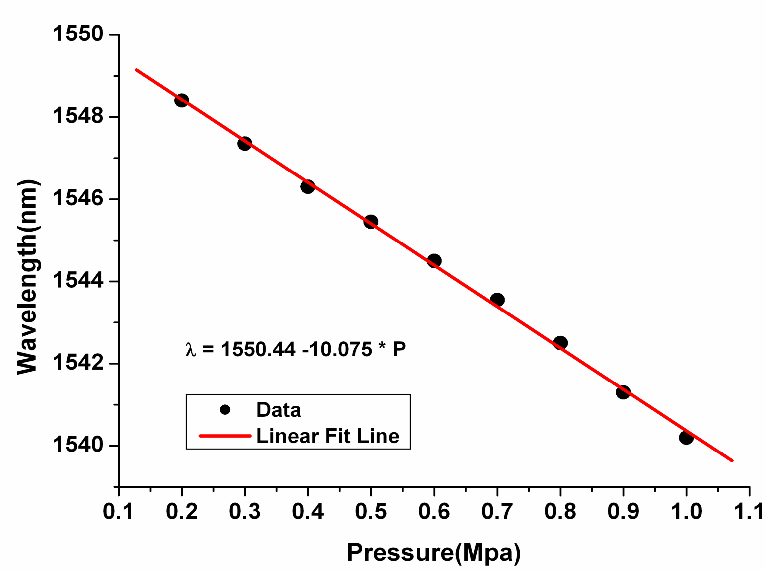

Fig.5 Measuring results of the pressure sensor

5. CONCLUSIONS

An optical MEMS pressure sensor based on the principle of Fabry–Perot interferometry has been demonstrated. The basic and simple micromachining techniques have been used to fabricate the pressure sensor. The shift of the reflected optical spectrum is used to measure the loaded pressure. The sensitivity and response range of this sensor are experimentally characterized to be 10.07nm/MPa (spectrum shift/pressure) and 0.2-1.0 MPa, respectively.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China, the Specialized Research Fund for the Doctoral Program of Higher Education (20050319007) and Jiangsu province high-novel technology project (BG2003024).

REFERENCES

1. Jie Zhou, Samhita Dasgupta, et al.. Optically interrogated MEMS pressure sensors for propulsion applications, Optical Engineering, Vol.40, No.4, April, 2001:598-604.
2. Don C.Abeysinghe, A Novel MEMS Pressure Sensor Fabricated on an Optical Fiber, IEEE photonics technology letter, Vol.13, No.9, September, 2001:993-995.
3. W.J. Wang, R.M. Lin, D.G. Guo, T.T. Sun, Development of a novel Fabry–Perot pressure microsensor, Sens. Actuators A 116 (2004):59-65.
4. Pawel Niewczas, Lukasz Dziuda, dt al.. Interrogation of Extrinsic Fabry–Pérot Interferometric Sensors Using Arrayed Waveguide Grating Devices, Vol.52, No.4, August, 2003:1092-1096.
5. L. Landeau and L. Lifschitz, Theory of Elasticity (Pergamon 1970).
6. Michael D. Baker, Frances R. Williams, A Novel In Situ Monitoring Technique for Reactive Ion Etching Using a Surface Micromachined Sensor, IEEE Transactions on semiconductor manufacturing, Vol. 11, No. 2, May, 1998:254-265
7. Kevin B. Albaugh ,Electrode Phenomena during Anodic Bonding of Silicon to Sodium Borosilicate Glass,J. Electrochem Soc. Vol 138, No.10, October, 1991: 3089 - 3094