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Design and Fabrication of Monolithic Photonic Crystal Fiber Acoustic Sensor

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Abstract

Single-crystal silicon is an excellent optical and mechanical material, but its properties are compromised by the incorporation of other materials required for functionality or structural support. Here we describe a monolithic silicon acoustic sensor based on a sensing diaphragm with an integrated Photonic Crystal (PC) mirror. Diaphragm deflection is measured in a Fabry-Perot resonator formed between the PC mirror and a gold coated single-mode fiber. The sensors are fabricated on standard silicon wafers by standard CMOS processing technologies, yielding monolithic, low-stress sensing diaphragms. The packaged sensor exhibits a minimum detectable pressure of $10 \mu\text{Pa}/\sqrt{\text{Hz}}$ in the 8 kHz to 17 kHz frequency range.

Keywords

Fabry-Perot; acoustic sensor; photonic crystal

I. INTRODUCTION

Acoustic sensors are used in many fields, such as structural health monitoring, medical imaging, oil exploration, and underwater communication. Fiber-based acoustic sensors have the advantages of high sensitivity, immunity to electromagnetic interference, and convenience of remote sensing. Many configurations of fiber acoustic sensors have been explored: fiber Bragg gratings [1], fiber lasers [2], Mach-Zender interferometers [3], Sagnac interferometers [4], and Fabry-Perot interferometers [5].

Fiber-based acoustic sensors utilizing Fabry-Perot interferometry have the advantages of high sensitivity, small footprint, and broadband operation. Previously, we reported on a FabryPerot acoustic sensor with a record low minimum detectable pressure of $5.6 \mu\text{Pa}/\sqrt{\text{Hz}}$ at 12.5 kHz [6], [7], [8]. However, the sensor requires silicon-on-insulator (SOI) wafers and a complicated assembly process.

Here we present a new fabrication process, enabling singlecrystalline silicon diaphragms with integrated PC mirrors on standard silicon wafers, as well as simplified packaging.

II. SENSOR STRUCTURE AND DEVICE FABRICATION

The basic principle of the sensor has been extensively discussed in [6], [7], [8]. To sum up, our sensor is a FabryPerot cavity on the facet of a single-mode fiber. The FabryPerot consists

of two mirrors: a fiber facet with gold coating for higher reflectivity and a PC mirror integrated on the sensing diaphragm.

A. Nanofabrication

Figure 1 illustrates the fabrication process of the sensing diaphragm with the integrated PC mirror: 1) Start with a standard p-type silicon wafer, 2) perform thermal oxidation, 3) pattern and etch the PC mirrors and assembly alignment trenches in oxide film, 4) etch directionally into silicon by reactive ion etch (RIE), 5) perform thermal oxidation for side wall protection, 6) etch directionally by RIE to remove oxide at the bottom of holes, 7) etch deeper into silicon by RIE, 8) under etch the PC mirror by isotropic silicon etch, 9) strip oxide by hydrofluoric acid (HF), 10) deposit nitride using low pressure chemical vapor deposition (LPCVD), 11) etch backside pattern into nitride, 12) etch the wafer anisotropically in potassium hydroxide (KOH), 13) strip nitride in hot phosphoric acid, 14) thin the sensing diaphragm to desired thickness by RIE.

Cross-sectional scanning electron microscopy (SEM) images of the sensing diaphragm at selected stages of the fabrication process are shown in Fig. 2. SEM images of the final device are shown in Fig. 3.

B. Sensor Assembly

The sensor assembly process is shown in Fig. 4. Four components are used in the process: a silicon chip with a sensing diaphragm (a), a quartz ferrule with a hole for stripped single-mode fiber (SMF) (b), a stripped SMF with 5 nm of chromium and 20 nm of gold evaporated onto the tip of the fiber (c), and a quartz tube (d). In the first assembly step, the ferrule is polished down by 450 μm on two sides (e) to create the backchannels that allow the acoustic pressure to fall primarily across the sensing diaphragm. Next, the SMF is fed through the ferrule and bonded with sodium silicate (f). In parallel, the silicon chip is mounted on the quartz tube. The alignment trench allows the tube to be inserted into the chip and then bonded by sodium silicate (g). Finally, the sensor assembly is completed by inserting the ferrule with the fiber into the tube, while monitoring the reflectivity from the fiber to fine tune the cavity length between the fiber tip and PC diaphragm to be around 31.6 μm . Once the desired cavity length has been achieved, the ferrule and tube are bonded with sodium silicate (h).

The diaphragm, chip and assembly dimensions are summarized in Table I.

III. SENSOR DESIGN

In this section, the design and optics of the PC mirror, mechanics of sensing diaphragm, and acoustics of the chamber are discussed in detail.

A. Photonic Crystal Design

The integrated PC on the sensing diaphragm is designed for high reflectivity for use as a mirror. Rigorous coupledwave analysis (RCWA) is used in the design to optimize the reflectivity of the PC and to test fabrication error tolerances. The structure of the designed

PC and its reflectivity are shown in Fig. 5. The result of the fabrication tolerance simulation of the thickness and diameter of the PC is shown in Fig. 6. The simulations show that the average reflectivity is above 0.9 for a thickness between 385 and 450 nm and a diameter between 740 and 775 nm. These ranges are well within the capability of our fabrication technology

B. Mechanical Characteristics of the Sensing Diaphragm

The single-crystalline sensing diaphragm is modeled using a finite element method (FEM) in COMSOL Multiphysics. The result is shown in Fig. 7. The fundamental resonance mode is at 35.9 kHz, and the second mode is at 138.5 kHz.

C. Acoustic Design

The acoustic properties of the sensor are studied by a lumped-element model. Given that the sensor dimensions are much smaller than the acoustic wavelengths up to 100 kHz, the lumped-element model can be used to study the sensor response and thermal-mechanical noise [9]. However, it only includes the fundamental mode of the diaphragm. For our design and application, we do not plan to operate above the fundamental mode. FEM models can be used to study the full interaction between the diaphragm and sensor acoustics at high frequency if required.

There are two modes of operation for the sensor. In the first mode, it operates as a normal microphone to probe signals from macroscopic objects. In this case, the acoustic signal also enters the sensor from the back channels (Fig. 8a). The second mode, the microscopic mode, is what this sensor is designed for. In this mode, a microscopic object (i.e. biological sample) will be positioned underneath the KOH etch hole on the backside of the wafer, and the acoustic signal will not reach the back channels (Fig. 8b).

The lumped-element model for microscopic mode is shown in Fig. 9: M_{rad} , R_{rad} , M_{dia} , and C_{dia} are radiation mass, radiation resistance, acoustic mass, and acoustic compliance of the diaphragm; M_{hole} and R_{hole} are acoustic mass and viscous resistance of the PC holes; R_{gap} is gap resistance from squeeze-film damping; and M_{chan} and R_{chan} are acoustic mass and viscous resistance of the back channels. The R_{gap} is split into two parts because the fiber facet is only facing a small fraction of the sensing diaphragm.

The radiation mass is the mass of the air moving along with the diaphragm when it oscillates:

$$M_{rad} = \frac{9\rho_a}{3\pi^2 r} \quad (1)$$

where ρ_a is the density of the air and r is the radius of the diaphragm. The radiation resistance is the kinetic energy dissipated into the fluid:

$$R_{rad} = \frac{\rho_a}{2\pi v_a} \omega^2 \quad (2)$$

where v_a is the speed of sound in the air and ω is the acoustic frequency. The acoustic mass of the diaphragm is calculated by an equivalent lumped mass representing the kinetic energy of the oscillating diaphragm:

$$M_{dia} = \frac{9h\rho'}{5\pi r^2} \quad (3)$$

where h is the thickness of the diaphragm, $\rho' = \rho(1 - p)$ is the effective density including the effect of PC holes, ρ is the density of the diaphragm material, p is the fill factor of the PC holes. The acoustic compliance of the diaphragm is calculated by an equivalent lumped spring representing the potential energy stored as displacement of the diaphragm:

$$C_{dia} = \frac{\pi r^6}{192D'} \quad (4)$$

where $D' = D(1 - p)(1 - 0.5\sqrt{p})$ is the effective flexural rigidity of the material. The PC hole viscous resistance has two sources: horizontal flow from the surroundings of the hole (squeeze-film flow) and the vertical flow of the fluid through the hole (Poiseuille flow):

$$R_{hole} = \frac{R_{hole, sff} + R_{hole, pf}}{N} \quad (5)$$

$$R_{hole, sff} = \frac{6\mu_a}{\pi L} \left(p - \frac{1}{4}p^2 - \frac{1}{2}\ln(p) - \frac{3}{4} \right) \quad (6)$$

$$R_{hole, pf} = \frac{8\mu_a h'}{\pi a^4} \quad (7)$$

where N is number of holes, μ_a is the dynamic viscosity of the fluid, L is the cavity length between diaphragm and fibertip, $h' = h + \frac{3\pi}{8}a$ is the effective thickness incorporating edge effects, a is the radius of the PC holes. The PC hole acoustic mass of the hole is:

$$M_{hole} = \frac{4\rho_a h''}{3\pi a^2} \quad (8)$$

where $h'' = h + \frac{2}{\pi} a$ is the effective thickness resulting from adding the radiation mass to the acoustic mass. The squeeze-film damping resistance of the gap between fiber and diaphragm is:

$$R_{gap} = \frac{3\mu_a}{2\pi L^4} \quad (9)$$

However, R_{gap} needs to be split into two parts because the fiber is smaller than the diaphragm. The ratio is $\alpha = \frac{r_f^2}{r^2}$, where r_f is the radius of the fiber. The viscous resistance and acoustic mass from the channels are:

$$R_{chan} = \frac{1}{n} \frac{8\mu_f L_{ch}}{\pi r_{ch}^4} \quad (10)$$

$$M_{chan} = \frac{1}{n} \frac{4\rho_f L_{ch}}{3\pi r_{ch}^2} \quad (11)$$

where n is the number of channels. Further details of the lumped-element model can be found in [7].

For the macroscopic mode, the ground on the right of the circuit is replaced by a source with phase lag. The phase lag is caused by the time it takes the signal to propagate along the tube to the top of the back channels.

The normalized sensitivity of the sensor determined by lumped-element modeling is shown in Fig. 10 for both modes of operation. The resonance for the sensor shows up at 14.6 kHz, which is lower than the mechanical resonance of the diaphragm itself at 35.9 kHz. This is due to the radiation mass (M_{rad}) and the acoustic mass of air in the back channels (M_{chan}) in Fig. 9. From the lumped-element model, the resonance of the diaphragm itself (M_{dia} and C_{dia}) is at 35.9 kHz, which is close to the result from COMSOL. By adding radiation mass (M_{rad}), the resonance shifts down to 22.8 kHz, because the mass of the air now oscillates with the diaphragm. The mass of air in PC holes (M_{hole}) is tiny and doesn't shift the resonance. Finally, the resonance shifts down to 14.6 kHz after adding the back channel (M_{chan}) into the model.

The lumped-element model also is used to calculate the thermo-mechanical noise of the diaphragm by (Fig. 11). The dominant terms are the noise in the diaphragm and the air flow in the back channels.

D. Optical Characterization

The different parts of the sensors were characterized in the optical setup shown in Fig. 12a. Broadband light (1520 nm to 1570 nm) is fed into Port 1 of an optical circulator through a single-mode fiber. Port 2 is connected to the samples, which can be the gold-coated fiber in the ferrule during assembly, a free space setup for measuring the PC reflection spectrum, or the assembled acoustic sensor. Port 3 is connected to an optical spectrum analyzer (OSA) to record the reflection spectra, as shown in Fig. 12b. The fiber and PC mirror have reflectivities around 63% and 88% respectively. The assembled sensor shows a Fabry-Perot reflection minimum centered at 1558 nm with a maximum slope of 3.17 %/nm between 1553 nm to 1557 nm. The Fabry-Perot reflectivity spectrum here is asymmetric, which is fully discussed in [11]. Furthermore, the reflection spectrum is strongly affected by the phase gradient of the PC mirror [12], [13]. These phase effects are important in the cavity design and affect the location of the maximum slope.

E. Acoustic Characterization

Acoustic characterization is performed on the assembled sensor as shown in Figure 13a. A tunable laser is tuned to 1555 nm, a wavelength of maximum slope and highest sensitivity in the Fabry-Perot spectrum. The tunable laser is connected to Port 1 of the circulator, Port 2 is connected to the acoustic sensor, and Port 3 is directed to a photodetector. An acoustic isolating chamber encloses our acoustic sensor, a reference microphone, and a speaker. The speaker is driven by a dynamic signal analyzer (DSA), and the signals from our sensor and reference sensor are connected to DSA. The sensitivity, noise, and minimum detectable pressure (MDP) spectrum are shown in Fig. 13 b-d.

IV. DISCUSSION

Due to the size limit on the speaker and characterization setup, the sensor can only be tested in macroscopic mode. The measured sensitivity curve in macroscopic mode shows low sensitivity at low frequency, as predicted by the lumpedelement model. The resonance peak is at 14.1 kHz, which is close to the 14.6 kHz predicted by the model. The measured Q factor is lower than that of the model. This can be explained by the model's underestimate of the viscous resistance. The model also doesn't include modes above the fundamental mode, which shows up at 32.8 kHz in the measurement.

The results from the lumped-element simulation are used to calculate the estimated performance of the sensor in microscopic mode. Here, the low sensitivity at low frequency characteristics are gone, and the sensitivity is closer to constant in the low frequency range. The peak and valley around 200Hz to 400Hz is from the acoustic resonance in the acoustic test chamber.

The COMSOL simulations (Fig. 7) show that there are higher order modes for the sensing diaphragm. However, the compliance at high frequency drops quickly above the

fundamental resonance. Furthermore, the wavelength of the acoustic wave is large compared to the diaphragm. It is 24.1 mm at 14.1 kHz, 9.5 mm at 35.9 kHz and 2.5 mm at 138.5kHz, which are all much larger than the diaphragm diameter of 392 μm . Given the low compliance and the wavelength larger than the diaphragm, the higher order modes are not excited to a significant level. Moreover, this sensor is designed to detect small signals in the microscopic mode, so the nonlinear mechanical effects are small and not significant for the intended operation.

There is strong $1/f$ noise from low frequencies up to 8 kHz. Through testing, it was determined that the noise stemmed from environmental acoustic noise coupled into the polarization states of the fiber components. A polarization-maintaining (PM) single-mode (SM) fiber system is recommended to replace our standard SM fiber system.

MDP in the microscopic mode average to around $492.9 \mu\text{Pa}/\sqrt{\text{Hz}}$ between 100 Hz to 1 kHz and $70.6 \mu\text{Pa}/\sqrt{\text{Hz}}$ between 1 kHz and 10 kHz. It reaches a minimum of $2.25 \mu\text{Pa}/\sqrt{\text{Hz}}$ at 14.1 kHz. The practical range of operation for this sensor is from 10 Hz to 30kHz. At low frequency, the $1/f$ noise from the optical system dominates. At high frequency, sensitivity drops after passing the fundamental mechanical resonance. Both of these lead to a high MDP for the sensor outside the practical operation range.

The thermo-mechanical noise limited MDP predicted by the lumped-element model is also shown in Fig. 13d. It shows $46.7 \mu\text{Pa}/\sqrt{\text{Hz}}$ MDP around the resonance. However, because our sensor has a lower Q factor than the model, the noise spectrum here is overestimated at the resonance. By correcting the model with more viscous resistance, the thermo-mechanical noise limited MDP at resonance is brought to $11 \mu\text{Pa}/\sqrt{\text{Hz}}$.

V. CONCLUSION

We have designed, fabricated, and characterized an acoustic sensor based on a sensing diaphragm of single-crystalline silicon with an integrated PC mirror. The fabrication process is based on standard silicon wafers, which are less expensive and of higher and more uniform quality than SOI wafers. The sensor is designed for simple assembly using a mechanical alignment trench for the critical chip-to-ferrule bonding. The sensor shows low MDP below $10 \mu\text{Pa}/\sqrt{\text{Hz}}$ between 8 kHz to 17 kHz, which is close to the thermo-mechanical noise limited MDP. This ultra-sensitive acoustic sensor is designed to study small biological samples in the microscopic mode.

For higher frequencies, the MDP is around $22 \mu\text{Pa}/\sqrt{\text{Hz}}$ due to the loss of sensitivity above the fundamental resonance. For lower frequencies, the MDP is limited by $1/f$ noise, which can be reduced by going to a PM fiber system.

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Biography

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Olav Solgaard Olav Solgaard earned his Ph.D. degree from Stanford University in 1992. His doctoral dissertation: “Integrated Semiconductor Light Modulators for Fiber-optic and Display Applications” was the basis for the establishment of a Silicon Valley firm Silicon Light Machines (SLM), co-founded by Dr. Solgaard in 1994. From 1992 to 1995 he carried out research on optical MEMS as a Postdoctoral Fellow at the University of California, Berkeley, and in 1995, he joined the Electrical Engineering faculty of the University of California, Davis. His work at UC Davis led to the invention of the multi-wavelength, fiber-optical switch, which has been developed into commercial products by several companies. In 1999 he joined Stanford University where he is now a Professor of Electrical Engineering and the Director of Graduate Studies in the Department of Electrical Engineering. Professor Solgaard’s research interests include optical MEMS, Photonic Crystals, optical sensors, microendoscopy, atomic force microscopy, and solar energy conversion. He has authored

more than 350 technical publications and holds 75 patents. Professor Solgaard is a Fellow of the IEEE, the Optical Society of America, the Royal Norwegian Society of Sciences and Letters, and the Norwegian Academy of Technological Sciences.

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Figure 1.
Monolithic photonic crystal acoustic sensor process flow.

Figure 2.
SEM cross-section (diaphragm surface tilted 52°) after a) Step 9 and b) Step 10.

Figure 3.

SEM images of the final device: a) Photonic crystal diaphragm on front side. b) KOH etch profile on backside. The Moiré pattern on the diaphragm is an artifact of the imaging and does not indicate physical variation across the diaphragm. c) Zoom-in on photonic crystal diaphragm on front side. d) Cross-section at the edge of the KOH etch intersection on the diaphragm (diaphragm surface tilted 52°).

Figure 4.
Sensor assembly.

Figure 5. Photonic crystal mirror: a) PC structure: pitch (p), thickness (t), diameter (d), b) Simulated reflectivity.

Figure 6.

Average reflectivity of the PC mirror between 1500 nm to 1600 nm with different thickness (t) and diameter (d). pitch ($p=900$ nm) is defined by the lithography mask.

Figure 7.
Mechanical Compliance of the sensing diaphragm.

Figure 8.
Modes of operation of the sensor: a) macroscopic mode, b) microscopic mode.

Figure 9. Lumped-element electromechanical circuit model. (The sensor drawing is not to scale.)

Figure 10.
Normalized sensitivity from lumped-element model.

Figure 11.

Calculated thermo-mechanical noise spectrum of the sensor: total noise and noise contributions from different elements.

Figure 12.

Optical characterization a) Experimental setup, b) Reflection spectra of the PC mirror, the Au-coated single-mode fiber in the ferrule, and the completed sensor.

Figure 13. Acoustic characterization a) Experimental setup, b) Sensitivity, c) Noise, d) Minimum detectable pressure (MDP)

Table I

SENSOR DEVICE DIMENSIONS

Physical Description	value
diaphragm thickness	450 nm
diaphragm diameter	392 μm
PC pitch	900 nm
PC diameter	760 nm
chip size	5 mm $\times$ 5 mm
tube outer diameter	2.8 mm
tube inner/ferrule outer diameter	1.8 mm
tube length	4 mm
ferrule length	5.5 mm
ferrule polish depth	450 μm
cavity length	31.6 μm