Miniature all-silica optical fiber pressure sensor with an ultrathin uniform diaphragm

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Abstract: This paper presents an all-silica miniature optical fiber pressure/acoustic sensor based on the Fabry-Perot (FP) interferometric principle. The endface of the etched optical fiber tip and silica thin diaphragm on it form the FP structure. The uniform and thin silica diaphragm was fabricated by etching away the silicon substrate from a commercial silicon wafer that has a thermal oxide layer. The thin film was directly thermally bonded to the endface of the optical fiber thus creating the Fabry-Perot cavity. Thin films with a thickness from 1μm to 3μm have been bonded successfully. The sensor shows good linearity and hysteresis during measurement. A sensor with 0.75 μm-thick diaphragm thinned by post silica etching was demonstrated to have a sensitivity of 11 nm/kPa. The new sensor has great potential to be used as a non-intrusive pressure sensor in a variety of sensing applications.

OCIS codes: (060.2370) Fiber optics sensors; (120.2230) Fabry-Perot; (230.3990) Micro-optical devices; (230.4685) Microstructure devices.

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1. Introduction

Optical fiber acoustic and pressure sensors have been widely used in industry and research in such fields as process control, environmental monitoring, nondestructive structural health monitoring, blast characterization, and voice communication [1–15]. Fabry-Perot (FP)-based miniature optical fiber sensors, utilizing a thin flexible diaphragm as a sensing element, are commonly used due to their high sensitivity, compact size, and survivability in harsh physical and chemical environments [6,9–11,16,17].

Prof. Esashi's group developed a thermal bonding method to fabricate an ultra miniature fiber optic pressure sensor on the tip of an optical fiber [18]. The polyimide spacer is used to connect the silica thin film and the optical fiber endface via thermal bonding. The polyimide's properties are greatly influenced by temperature and usually it has a larger thermal expansion coefficient than either silicon or silica. Therefore, this limits its use in high temperature applications or widely fluctuating temperature conditions. Cibula and Donlagic reported on a miniature optical fiber pressure sensor using a polymer as its diaphragm [19]. The diaphragm can be thinned down to a few microns and is thus suitable for mass production. However, for under water measurement applications, the polymer must be kept in water for a long period of time to stabilize before it can be used, due to its tendency to absorb water. Meanwhile, due to the porous cellar structure of the polymer, the diaphragm cannot be fabricated too thin and is not suitable for long-term pressure measurement. Abeysinghe et al. reported a compact optical fiber sensor with an ultra thin silicon diaphragm anodically bonded on the endface of the optical fiber [3]. This technology was further improved by bonding the ultrathin silicon wafer to a thick silicon wafer [20]. The thickness of the silicon diaphragm is usually larger than 3 μm and standard optical fiber used in optical communication cannot be used due to its lack of alkaline ions. The fabrication process is also complex and expensive because of the need for introducing an electrode on the fiber side surface as well as the end-face during preparation and alignment required for anodic bonding. This complex fabrication method greatly increases production cost. The material used to make the thin film is different from the material comprising the fiber. Therefore, the different coefficients of thermal expansion can lead to sensing errors.

Recently, all fused-silica optical fiber sensors were developed. Prof. Wang's group reported a fabrication method of laser fusion bonding [8]. Using this method, a thin fused silica diaphragm and an optical fiber are bonded to a ferrule. This type of device has a wide range of working temperatures in addition to outstanding temperature stability. The splicing-and-cutting method is another popular method used to fabricate optical fiber sensors [6,10,11,16,17]. An optical fiber is spliced on a cavity-formed fiber first. Then it is cut near the spliced position to form a diaphragm. The thickness of the diaphragm is further reduced by post hydrofluoric acid (HF) etching. The diameter of the whole sensor is equal to the

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diameter of the optical fiber. The diaphragm is also fused-silica which leads to outstanding thermal performance because of identical coefficients of thermal expansion. In another fabrication method, the thickness of the diaphragm is controlled by post polishing and in-line monitoring during the HF etching [16,17].

In this paper, we present a novel fabrication method that results in the production of sensors with ultra-thin, highly uniform and reproducible silica diaphragms. The results from several experiments are presented to demonstrate the performance of the sensors. The new sensors are well suited to be used in applications (bio-medical, structural health monitoring, blast measurement, etc.) where a lightweight and non-intrusive pressure sensor is required. To the author's knowledge, the direct thermal bonding between silica thin film and the end face of an optical fiber has not been previously reported in the literature. This method can increase the thin film uniformity and reduce the minimum thin film thickness within a single sensor while increasing the manufacturing repeatability from one sensor to the next, compared with other currently available fabrication methods. This work also presents the thinnest thickness diaphragm that currently exists. The thinner diaphragm will lead to a higher sensitivity and faster response for the sensor. Additionally, the method reported in this work also provides a more efficient fabrication process compared with methods that rely on post polishing and in-line monitoring during the HF etching to control the thickness of the diaphragm. The novel approach the authors propose will lead to efficient mass-production, improved manufacturability, and can greatly reduce the cost to fabricate individual sensors that have improved performance.

2. The method of sensor fabrication

The fabrication method presented in this paper involves thermal-bonding of a thin silica film directly onto the endface of a silica optical fiber. The optical fiber cavity was fabricated using the splicing and etching method in [17]. Because spectrum shift monitoring method is used to test the sensor using a spectrometer (wavelength range: 1520 nm - 1570 nm), fibers with good cavity surface and cavity length (approximately 20 μm - 40 μm) were selected to fabricate the sensor in order to produce a good low finesse fringe having at least one peak (or valley) in the fringe within the instrumental wavelength range. Yield of the fiber tip with the cavity can be improved by using a stop layer [10]. A commercially available silicon wafer with thermal oxide is used to prepare the silica thin film. Silicon of the silica-on-silicon wafer is etched away by silicon deep reactive ion etching (RIE). The wafer can be patterned with a circular open window before the etching is performed in order to keep some silicon substrate as a framework to hold the thin oxide layer. When the silicon is etched away, the remaining oxide film is then ready to be bonded to the optical fiber tip. The bonding process is shown in Fig. 1. First, the silica thin film is placed between an optical fiber tip which is enclosed within a standard single mode Zirconia ferrule (ID 128 μm, Kientec Systems, Inc) and a Zirconia ceramic holder with plan surface (Kientec Systems, Inc), as shown in Fig. 1(a). A 100 μm – 500 μm optical fiber tip was exposed out of the ferrule to minimize the heat damage and prevent bending from occurring while applying the required force. Second, a standard propane torch (sold by ACE hardware corporation) was used to heat up the fiber while it is pressed against the silica thin film using a stage as shown in Fig. 1(b). The fiber is placed within the stage approximately 15 mm away from the fiber's tip and had a traveling distance ranging from 20 μm to 50 μm. After a few seconds, the thermal bonding process is completed as shown in Fig. 1(c). Third, the fiber is passed through the ferrule. The oxide film that is located beyond the area of the endface of the optical fiber is then cut away, as shown in Fig. 1(d). The edge may contain a small portion of thin film outside the fiber tip due to the mismatch between the diameter of fiber and the inside diameter of the ferrule, or the diaphragm may be peeled off due to the imperfect bonding as shown in Fig. 2(a). The silica thin film can also be removed by hydrofluoric acid etching because of the double-side etching for any area that is not covered by the optical fiber. However, this method is limited to

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fabrication of thinner diaphragm because of the weak point between diaphragm and optical fiber has higher etching speed which can cause the diaphragm to break more quickly.

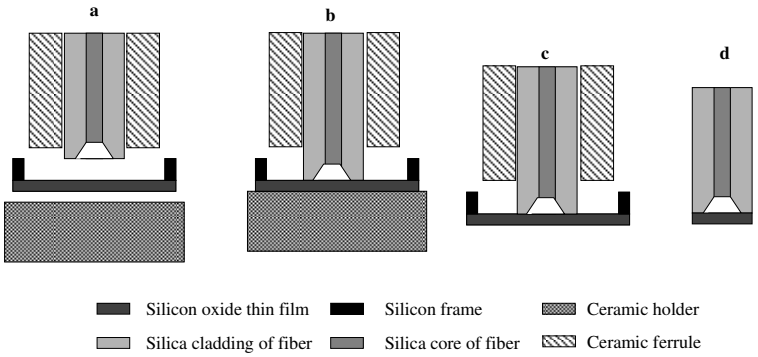

Fig. 1. Schematic process of the direct bonding of silica thin film.

Figure 2 shows the microscopic pictures of the fiber tip bonded with silica thin film. Figure 2(a) shows a fiber tip with a 1-µm-thick silica diaphragm after cutting away the extra thin film and Fig. 2(b) shows a tip with a 3-µm-thick diaphragm before removing the extra thin film. The center area in Fig. 2(a) shows the suspended diaphragm. The outer annular region represents the bonded area. From the image of the diaphragm, it can be seen that the diaphragm is smooth and uniform. The bright spot seen at the center of the diaphragm is caused by the light guided and reflected by the single mode optical fiber. The upper part of the fiber was cracked due to the excessive force used during the bonding process. Figure 2(b) shows perfect bonding of the diaphragm to the fiber without any visible defects.

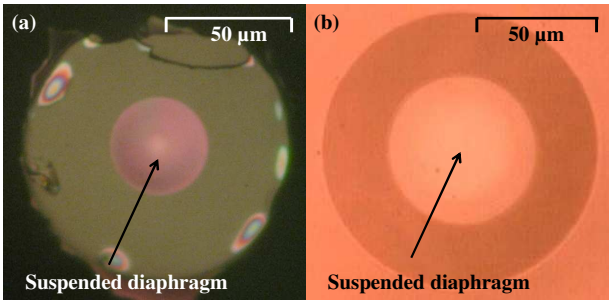

Fig. 2. Photomicrograph of the fiber tip with bonded diaphragm. (a) fiber tip with a 1 µm-thick diaphragm and (b) fiber tip with a 3 µm-thick diaphragm.

Figure 3(b) shows the Focused Ion Beam (FIB) image of the fiber tip bonded with the 3 µm-thick silica diaphragm, following 12 minutes of etching by Buffered Oxide Etch (BOE, Ammonium fluoride solution (40%):Hydrofluoric Acid (49%) = 7:1). The thickness of the remaining diaphragm is approximately 2.2 µm after etching. The excess silicon oxide film beyond the area of the optical fiber tip has not been removed. Figure 3(b) shows the entire milling area and the sensor head. The diaphragm was coarse milled first to introduce an opening and then the fabrication followed with a fine milling on the lower edge at the opening. However, The cutting edge of the fine milling is not perpendicular to the diaphragm but has a slope that can be seen at the starting and ending locations. Due to the imperfect milling, the thickness of the cut diaphragm shown in Fig. 3(b) is larger than the desired thickness. However, this imperfect milling does not influence the capability of the image to identify the uniformity of the diaphragm. The thickness of the diaphragm beyond the bonding area is less than that of the bonding area due to the double side etching. The bonding interface has much faster etching speed due to the stress introduced during the high temperature

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bonding process. It can be reduced by post annealing which has not been done for these samples. The small dents at the bonding area are caused by the imperfect surface of the holder. There are no dents on the suspended diaphragm and the small imperfections on the bonding area do not influence the performance of the sensor. Figure 3(a) shows the bonding area between fiber and a 3 μm thick diaphragm with good milling result. The bonding appears optimal and no visible defects are seen. From Fig. 3(a) and Fig. 3(b) we can see that the diaphragm is smooth, flat and uniform.

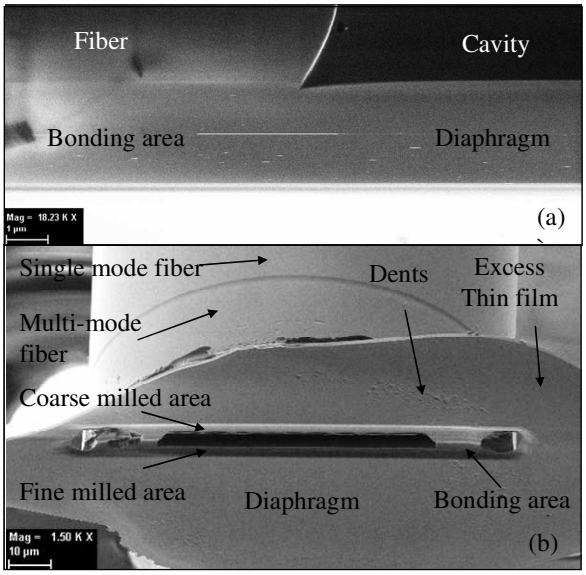

Fig. 3. FIB image of the cross-section of the diaphragm and the bonding interface of the intermediate stage sensor. (a) the enlarged image of the bonding area between diaphragm and optical fiber (b) the whole picture of the milling area and the sensor head.

Using silicon oxide thin film grown on a silicon wafer as the diaphragm material and transferring it to the end face of optical fiber using thermal bonding offers several outstanding advantages compared with other all silica fiber sensors discussed in section 1: (a) Reliable production of thin and uniform diaphragms. Because the thin silica film is made by thermal oxidization of silicon, the film can be thinned down to submicron size and is very uniform in thickness. Therefore, the sensor may have higher sensitivity (which is dependent upon the thickness) even though the diameter of the diaphragm may be limited by the diameter of the optical fiber; (b) Good reproducibility which is essential for mass fabrication. The repeatability of the thickness of thin film is expected to be within 5% of the nominal value, which results from the well-developed fabrication process of silica thin film based on established Micro-electro-mechanical System (MEMS) technology. Three sensors with optical fiber tips and diaphragms etched within the same batch show the sensitivity deviation of the diaphragm deformation (before BOE modification) to be 3.7%; (c) An extensive range of diaphragm thicknesses. The thickness of the oxide layer of commercially available silicon wafers can range from a few nanometers up to 10 microns. This creates a large number of choices for the silica-on-silicon wafer to be selected. At the same time, the thickness can be fine-tuned by post HF etching and is benefited from the uniformity of the diaphragm; (d) Low cost for mass production of the sensors. The fabrication process is simple and suitable for mass fabrication with excellent reliability, reproducibility, and quality control.

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3. Experiments and discussion

The optical sensor was tested side by side with a commercially available pressure transducer (Omega, PX303-030G5V) in a pressure chamber. The output of the Omega reference pressure sensor was assumed to be the true pressure value applied to the testing chamber while evaluating the performance of the new optical fiber sensor. The reflection spectrum of the fiber sensor was measured by a swept laser interrogator (1520 nm - 1570 nm, Component Testing System, Micron Optics) at 2 pm resolution with a 1 kHz low pass filter. The spectrum position and the output of the reference sensor were continuously collected by a data acquisition system while the chamber pressures were being changed. Finally, the spectral shift observed was converted to a correspondingly proportionate diaphragm deflection based on the interferometry principle. Because the reflectivity at two surfaces of the diaphragm are similar when the sensor is used in air, the reflections of the diaphragm will interference each other and may give a combined reflection with much different intensity from the reflection at the optical fiber end face within the measurement wavelength range. In order to obtain a good low finesse fringe, which requires that the two reflections have similar intensity, the thickness of the diaphragm was adjusted slightly by BOE (7:1) etching. Figure 4 shows a typical reflection spectrum after the thickness adjustment. An optical fiber sensor with a diaphragm thickness 2.2 μm and diaphragm diameter of about 65 μm was tested. Two pressure cycles (increasing and decreasing) were recorded. Calibrated pressure and the residual between optical sensor and reference sensor are shown in Fig. 5.. The minor decreasing of the residual may be caused by the thermal drift of the senor. The average values of first cycle of pressure changes are used to determine the results shown in Fig. 6 to demonstrate the linearity, sensitivity, and hysteresis of the measurements made by the sensor.. The sensor sensitivity is approximately 1.16 nm/kPa. The linearity is good with a correlation coefficient (R) of 0.99996. The maximum difference for bidirectional running for a given pressure is 0.345 nm which indicates the sensor has a maximum hysteresis of approximately 0.3%.

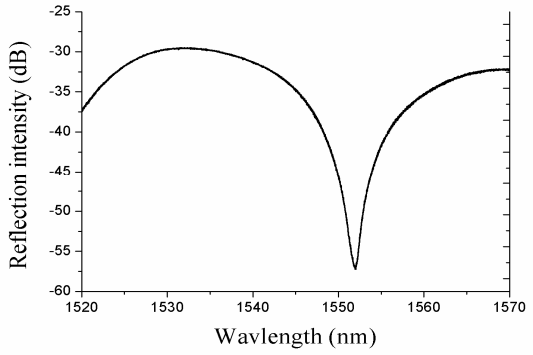

Fig. 4. The reflection spectrum of the sensor with approximately a 2.2 um thick diaphragm.

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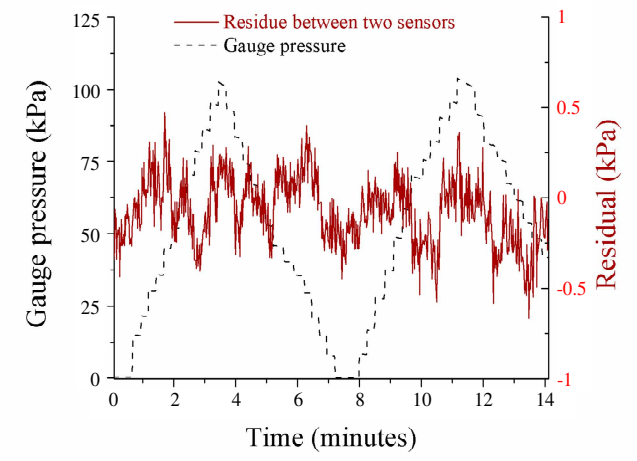

Fig. 5. The gauge pressure by calibrated optical fiber sensor for two pressure changing cycles (dotted line). Red curve shows the residual between optical sensor and reference sensor which is very small.

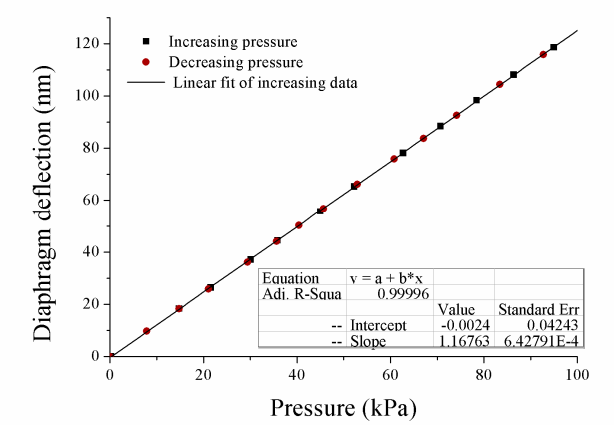

Fig. 6. Linearity and hysteresis of the sensor after 20 minutes of BOE etching.

Because the thin silica diaphragm is made of the thermal silicon oxide grown on the silicon wafer, the diaphragm thus has uniform material composition and thickness. Unlike other approaches [16,17], additional surface treatment process, such as polishing, is needed to smooth the surface. The uniform and smooth diaphragm can be further thinned by HF etching. Fine tuning of the fabrication process thus described produces an extensive range of potential diaphragm thicknesses and much thinner diaphragms can be fabricated. An optical fiber sensor with a 3μm thick silica diaphragm was etched in buffered-oxide etchant (BOE) to demonstrate this capability. Figure 7 shows the sensitivities of the same sensor after a serial BOE etching. Pressure ranges for each test are 140 kPa, 120 kPa, 20 kPa and 7 kPa, respectively, in which the authors believe the sensor is operating within a linear zone [16]. After about 20 minutes of BOE etching, the sensitivity was increased to approximately 11 nm/kPa which is comparable with that reported in [16]. The thickness of the diaphragm is only 0.75 μm, which is the thinnest diaphragm reported in the literature among all all-silica miniaturized optical fiber sensors. Even without post fabrication HF-etching, the 1 μm-thick uniform and smooth silica diaphragm that is being demonstrated is still the best available with the ability to be reproduced via mass production.

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The thermal dependent diaphragm displacement of a senor with sensitivity of 2 nm/kPa was tested in a temperature controlled chamber and the results are shown in Fig. 8. The thermal dependant diaphragm displacement is approximately 0.28 nm/°C. This is mainly due to the thermal expansion of the air sealed inside the cavity. If vacuum fabrication process is used, the thermal drift will be reduced greatly because the fiber and the diaphragm are all silica and have similar thermal expansion coefficients.

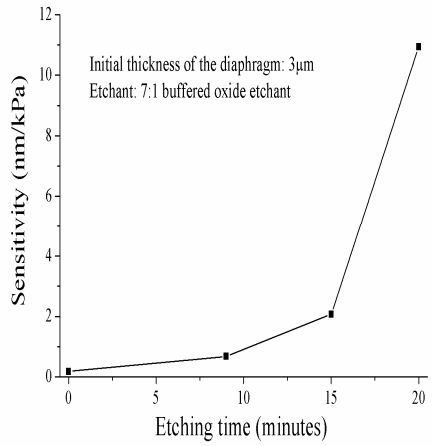

Fig. 7. Sensitivity of the pressure sensor for different etching times in 7:1 BOE.

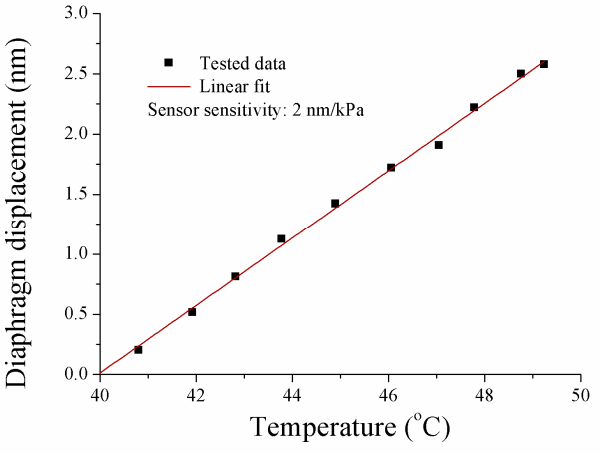

Fig. 8. Temperature dependant diaphragm displacement.

4. Conclusion

An all-silica miniature FP-type optical fiber pressure/acoustic sensor was designed, fabricated and tested using a novel process. The silica diaphragm was fabricated from the thermal oxidized silicon wafer and was thermally bonded directly on the optical fiber tip enclosing the FP-cavity. Diaphragms with thicknesses between 1 μm to 3 μm have been successfully bonded to the optical fiber endface. Photomicrographs taken by optical microscope and FIB microscope show that the diaphragms are smooth and uniform in shape and the bonding quality appears excellent based on the visual evidence. One of the typical sensors thus fabricated was tested alongside a commercially available pressure sensor. The results of these tests show that the novel fiber optic pressure sensor has very good linearity and hysteresis in the measurements that were made. An optical fiber sensor with 3 μm-thick silica diaphragm

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was etched in BOE to demonstrate the ability of making post-fabrication adjustments to the diaphragm thickness. This enables the manufacturing of sensors having a large range of varied thickness without any significant surface preparation. A sensor having a 0.75 μm thick diaphragm and 11 nm/kPa sensitivity was demonstrated. The novel process for fabrication of an optical fiber sensor fabricated by using the thermal bonding method presented here features several outstanding advantages including high sensitivity and reproducibility, low cost, and the ability to be fabricated in a mass production setting.

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