A miniaturized fiber-optic pressure sensor 125μm in diameter has been developed for the measurement in human body
[1]. The sensing element is fabricated by micromachining, and attached to the end of an optical fiber using polyimide
adhesive layer. A Fabry-Perot interferometer is constituted of a half-mirror at the fiber end and a reflection mirror on the
movable thin diaphragm. The intensity of the light reflected at the interferometer is modulated by the pressure, because
the optical path difference between the two mirrors of the interferometer varies with the displacement of the diaphragm
in dependence on the pressure.

Keywords: Optical fiber, Pressure sensor, Silicon micromachining, Interferometer, Catheter

1. Introduction

Pressure measurement in blood vessel is required at clinical site, as it brings useful information for medical diag-
nosis and treatment.

For monitoring accurate pressure, some catheter tip pressure sensors which have a sensing element at the end of
the catheter have been developed. Commercialized catheter tip pressure sensors are mainly piezoresistive or fi-
ber-optic [2,3].

Piezoresistive sensors are popular, but expensive, so it is hard to make them disposable. They are not small
enough for various medical applications. Such electrical sensors have risk of electrical hazard in the human body,
and are susceptible to the electromagnetic interference by various electrical equipments in an operating room.

On the other hand, such problems can be solved by fiber-optic type sensors. They can be inexpensive, extremely
small size and free from an electrical hazard. We have developed an ultra-miniature fiber-optic pressure sensor
which has a sensing element at the end of an optical fiber. The sensor element is made of a thin diaphragm. The
diameter of the sensor element is smaller than 125μm, which is that of the optical fiber. This is the smallest cath-
eter tip sensor for the present. The sensor element is fabricated using silicon micromachining, which enables mass
production and hence disposable use. Optical signal traveling through a optical fiber is not affected by an electro-
magnetic interference.

2. Structure of sensor

The structure of the fiber-optic pressure sensor is shown in Fig.1. The sensing element is composed of a thin sili-
con dioxide diaphragm with a mesa, an aluminum mirror on the mesa and a polyimide spacer, is fabricated by sili-

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con micromachining. It is attached to the end of the multimode optical fiber using the polyimide spacer as the adhesive layer. The outer diameter and the core diameter of the optical fiber are 125μm and 50μm respectively. The half-mirror is formed at the end of the optical fiber by vacuum evaporation of ZnS (zinc sulfide). The thickness of the half-mirror is optimized to obtain large interference signal. The silicon dioxide diaphragm is 0.7μm thick and is formed by plasma CVD using TEOS (TetraEthOxySilane) source. The thickness of the diaphragm was determined for the required measurement range of the sensor (0-300mmHg). The diaphragm is 120μm in diameter and has a mesa formed with a thick silicon dioxide at the center of the diaphragm. The mesa is 2.3μm thick and 60μm in diameter and has an aluminum reflection mirror on it. Owing to the thick mesa, the reflection mirror is kept flat under applied pressure. The thickness of the ring-shaped spacer made of photosensitive polyimide is approximately 5μm which is determined to keep the required optical pass between two mirrors, a Fabry-Perot interferometer is constituted at the fiber end. The spacer is 90μm and 120μm in inner and outer diameters and 5μm in thickness. Light from a laser diode travels in the optical fiber to the sensing element, and is reflected at two mirrors. The reflected light travels back to a photodetector through a coupler, and the photointensity is monitored.

3. Working principle

The working principle is shown in Fig.2. The deformation of the diaphragm induced by the pressure varies the optical path between two mirrors. The reflected light is modulated interferometrically because the phases of two lights reflected at the half mirror and the reflecting mirror have differences in dependence on the pressure. The pressure can be monitored by detecting the intensity of the reflected light with a photo detector. The interferometrical modulation can be maximized by tuning the wavelength of the light from the laser diode.

4. Fabrication of sensor

The sensor was fabricated by three processes. First, the sensing element is made by silicon micromachining. Second, the end of the optical fiber is coated ZnS half-mirror layer and the sensing element is attached to the end of the optical fiber by our new bonding technique. At last, an unnecessary silicon part is removed by XeF₂ (xenon difluoride) silicon etching.

4.1 Fabrication of the sensing element

Fig.3 shows the fabrication process of the sensing element.

(1) Silicon dioxide film is deposited on both sides of a 200μm thick silicon wafer by plasma CVD using TEOS source. The film thickness of the topside is 2.3μm and that of the downside is 0.5μm. These silicon dioxide films are patterned for the mesa and

![Fig.2 Working principle](image)

![Fig.3 Process flow of the sensing element](image)
the etching mask used in the later silicon etching process.

(2) Silicon dioxide film (0.7μm thick) is deposited by atmospheric pressure CVD and the diaphragm is patterned.

(3) Aluminum is evaporated in vacuum and patterned by lift-off process for the reflecting mirror.

(4) The adhesive spacer is formed with photosensitive polyimide (Photoneece UR-3140, Toray Industries, Inc.). The polyimide is half-baked at 150°C.

(5) The silicon wafer is etched through the wafer by deep silicon RIE (Reactive Ion Etching).

As the result of this process, many silicon columns that have the sensing element on its end can be batch fabricated on a wafer as shown in Fig.4. The diameter of the silicon column is 120μm, and the height is 200μm which is equal to the wafer thickness.

Fig.5 is the SEM micrograph of the fabricated silicon column. The sensing element is observed at the end of the column.

4.2 Bonding

Bonding the sensing element to the end of the optical fiber is carried out with a glass micro capillary (Nippon Electric Glass Co. Ltd.) as a guide, which is generally used as an optical fibers connector. The capillary has 127μm inner diameter, which is slightly larger than the outer diameter of an optical fiber. The bonding process is shown in Fig.6. The silicon column with the sensing element and a micro bead (Nippon Electric Glass Co. Ltd.) with 100μm in diameter are inserted into the capillary. An optical fiber which has a half-mirror made of ZnS on its end is inserted into the capillary so as to be touched to the sensing element on the silicon column. A metal wire is inserted from the other side and used to push the polyimide layer on the sensing element to the fiber end. The capillary has tapered shape at both ends, and it is easy to insert these parts into the capillary. The micro bead is used to avoid unbalance of pushing force. The capillary is heated up to 350°C, and the silicon column including the sensing element is thermally bonded with the polyimide adhesive spacer to the fiber end [4].

4.3 Xenon difluoride silicon etching

The silicon column bonded to the end of an optical fiber is fully etched out by xenon difluoride etching [5] as shown Fig.7, and the only sensing element remains at the fiber end.
end. Since xenon difluoride silicon etching process has extremely high selectivity with other materials including silicon dioxide and polyimide, the sensing element is not damaged in this process.

Fig. 8 shows the SEM micrograph of the completed sensor, the small sensing element at the fiber end can be observed.

5. Results and discussion

The measuring system shown in Fig. 9 is used to test the pressure sensor. The laser diode of 694nm wavelength is used as the light source. The laser light is collimated by lens, transmitted through the beam splitter, and comes into the optical fiber which has the sensing element at the other end after condensed by a lens. The light travels in the optical fiber, and is reflected at the small interferometer at the fiber end. The reflected light returns in the same fiber, comes into a spectrum analyzer through the
beam splitter and an aperture. The photointensity of the reflected light is monitored. The laser light travels in a multimode optical fiber with dispersing phase due to its mode dispersion. This makes the visibility (degree of intensity modulation) small. To decrease the effect of the mode dispersion and obtain high visibility, the excessive optical mode of the reflected light is cut off by the aperture as shown in Fig.9. The central part of the reflected light is selectively detected, because it is less affected by the mode dispersion. The sensing part of the pressure sensor is put into the pressure chamber, and the sensor is characterized. The applied pressure was swept from \(-300\) to \(+300\)mmHg, and the reflected light intensity during the sweeping was monitored. The result is shown in Fig.10. The intensity varied periodically with the pressure increase. The degree of visibility in this figure was large enough, and was equal to 0.64. This result agrees with the general optical interference, and this demonstrates the interferometer (sensing element) at the fiber end functions as reflected pressure sensor.

The curve in this graph is different from normal sinusoidal curve. When the displacement of the diaphragm is large compared with the thickness, it is not proportional to the applied pressure. Fig.11 shows the relation of the displacement to the pressure simulated using thickness as parameter.

As shown schematically in Fig.12, the period of the sinusoidal curve is short when the diaphragm is flat, and it increases with the deformation of the diaphragm because of the reason shown in Fig.11.

The pressure at the flat diaphragm condition is similar to that in the cavity of the sensing element. The pressure in the cavity depends on the thermal expansion of the air in the cavity and the outgas from the adhesive polyimide layer during the bonding process. Therefore, the pressure at the flat diaphragm condition can not be well controlled. And the sensor is sensitive to temperature due to the fact that the cavity is not at vacuum but it sealed with air at ambient pressure. As sealing the cavity in vaccum is difficult using polyimide as a bonding layer, other bonding method is needed to seal the cavity in vacuum. If the sensor is used in blood vessel, sensitiveness to the temperature is not big problem because the temperature inside the body is maintained relatively constant.

The measurement system of the fiber-optic sensor using monochromatic light such as laser light is greatly affected by the bending or the vibration of the optical fiber. This can be solved by using white light source and measuring the shift of the peak of interference spectrum [6]. This working principle is expected not only to avoid the problem above, but also to extend the measurement range because the measurement range is not limited by the linear part of the sinusoidal curve in Fig.10. The resolution of the sensor can be also improved because it is not influenced by the fluctuation of the source light.

For the wide measurement range of the sensor, the diaphragm was deformed largely in proportion to the pressure is required. A corrugated diaphragm is suited for this purpose [7].
6. Conclusions

In this study, an ultra miniature 125μm diameter optical fiber pressure sensor was developed. The sensing element fabricated by micromachining was attached to the end of an optical fiber by our new bonding process using a glass capillary as a guide. After xenon difluoride silicon etching, the Fabry-Perot interferometer was obtained at the end of an optical fiber, and it could modulate the intensity of the light from a laser diode in dependence on the pressure.

By virtue of its small scale and electrical hazard free optical detection principle, this pressure sensor is expected to be used in blood vessel.

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