SPIRAL-TUBE PARYLENE INTRAOCULAR PRESSURE SENSOR

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ABSTRACT

This paper presents the first biocompatible, all-mechanical, micromachined pressure sensor with a high-aspect-ratio spiral-tube structure fabricated through a one-layer parylene process. This passive sensor has zero power consumption and indicates the pressure variation by changes of *in situ* in-plane spiral rotation, which can be gauged externally by a direct and convenient optical observation. A 1 mm-radius device with a 10-turn spiral has demonstrated a 0.22 degree/mmHg sensitivity in liquid. This device is designed for eye implantation and the intraocular spiral rotation can be recorded from outside of the eye. Such a sensing technology is proposed to monitor the intraocular pressure in glaucoma patients.

1. INTRODUCTION

Glaucoma is a debilitating disease that results in loss of vision for hundreds of millions of people worldwide. It is defined by damage to the optic nerve, the ultimate pathway for visual information after processing by the retina at the posterior aspect of the eye. Of the many risk factors for this optic neuropathy, perhaps the most significant is elevated intraocular pressure (IOP). Because IOP is strongly implicated in the pathogenesis of glaucoma, and because treatment involves lowering patients' IOP, methods of precisely monitoring real-time pressure changes are critical for treatment of this disease.

Current tonometry techniques involve indirect measurement of IOP. The tonometers used in common practice are difficult to implement for regularly monitoring pressure fluctuations and treatment progress. Many MEMS pressure sensor designs have been proposed [1] because the small scale of MEMS devices can be specifically applied to IOP sensing [2]. These microfabricated devices can provide accurate and precise pressure readouts, but all of them require electrical circuitry and hermetic sealing, a significant impediment to their implementation. For such IOP sensors, the major difficulties include both power consumption and biocompatibility issues. To realize a faithful IOP measurement inside the eye, a new sensing paradigm is proposed. It includes a passive, biocompatible micromachined pressure sensor. This sensor will be implanted under the cornea so IOP changes can be measured by using direct and economic optical equipments, such as stereoscopes and magnifiers. Advantages of this technology include low-cost, high portability, and ease-of-use. In fact, for daily recording of intraocular pressure, the sensor simply needs to be examined under an optical magnifier. This convenient sensing method can be used to carefully monitor and control a patient's glaucoma.

2. DEVICE DESIGN

The concept of the device (Fig. 1) is based on a Bourdon tube [3]. A free-standing spiral tube is formed by a long, thin-walled toroidal channel, with a pointing tip at the end for direct indication. This structure is supported by its connection to the central cylinder, which is fixed to the substrate. The pressure inside the hollow spiral channel is sealed at a designated constant. When a uniform pressure difference is generated across the channel walls, a bending moment is created. It forces an in-plane radial and angular deformation of the device. Out-of-plane deformation is negligible due to the geometrical shape. The deformation, which can be visualized by movement of the pointing tip, is linearly related to the pressure difference. Therefore, the corresponding environmental (outside-wall) pressure can be measured. The overall shape of the channel is an Archimedean spiral, of which the angular deformation indicated by the tip rotation can be amplified by increasing the number of coiled turns. In addition, a channel structure with thinner walls and higher aspect-ratio profile is more sensitive to environmental pressure change. These design factors must be considered to achieve high pressure sensitivity of the device.

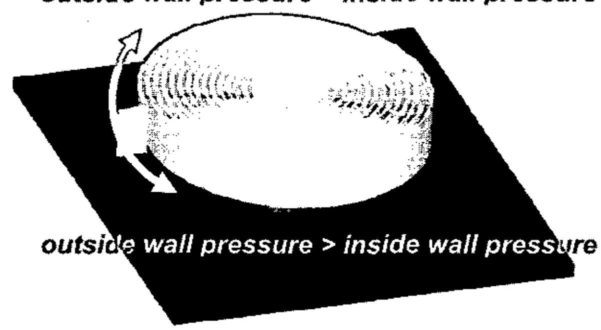


Figure 1: The conceptual device. An external pressure change is indicated by the rotation of the pointing tip.

Parylene (poly-para-xylylene) is selected as the structural material because of its desirable properties, such as high flexibility (Young modulus ~3 GPa), chemical inertness, and biocompatibility [4]. Moreover, parylene is compatible with microfabrication technology and can be deposited as a pinhole-free conformal coating at room temperature. It has been widely used in microfluidic and bioMEMS devices. Recently, the micromachining techniques and applications of high-aspect-ratio parylene structures have been successfully demonstrated [5]. This work develops another high-aspect-ratio channel structure using only one-layer of parylene deposition.

3. DEVICE FABRICATION

Process Flow

The fabrication process (Fig. 2) begins with 5000 Å wet oxidation on a standard silicon wafer. After patterning the oxide, a conventional Bosch process in a PlasmaTherm DRIE is used to etch trenches. SF_6 plasma etching is then performed to isotropically undercut the silicon surrounding the trenches. 75 μm deep, 6 μm wide trenches with 2.5 μm sidewall undercut can be created by using the above process (Fig. 3.a). Before parylene deposition, a short C_4F_8 deposition is performed to intentionally degrade the adhesion between the silicon and the parylene. Subsequently a 5 μm thick parylene layer is deposited. This conformal deposition concurrently seals the trenches to form the spiral channel (Fig. 3.b), the pointing tip, the surrounding indicators, and a parylene "web" structure at the center that supports the channel. The parylene is then patterned by using oxygen plasma. During this step, a thin opening ring is created in the center to prevent the complete sealing of the device. Finally, after photoresist and oxide removal, the spiral channel is released from the substrate by XeF_2 gaseous etching.

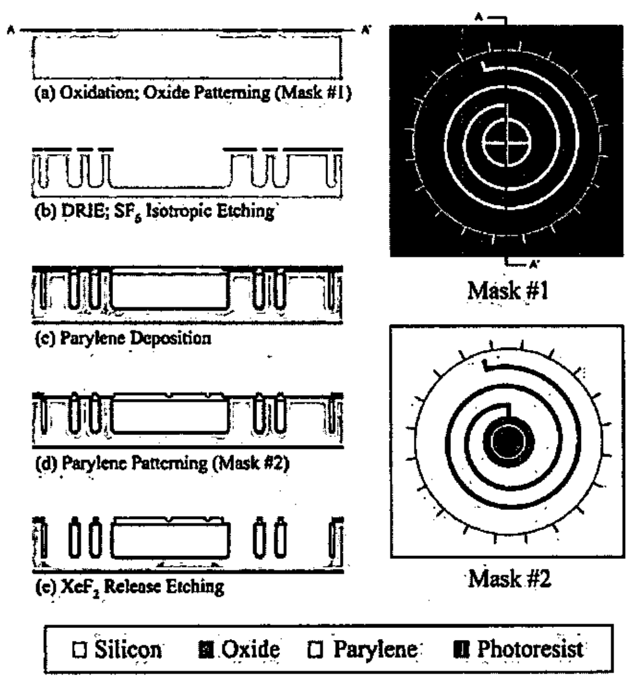
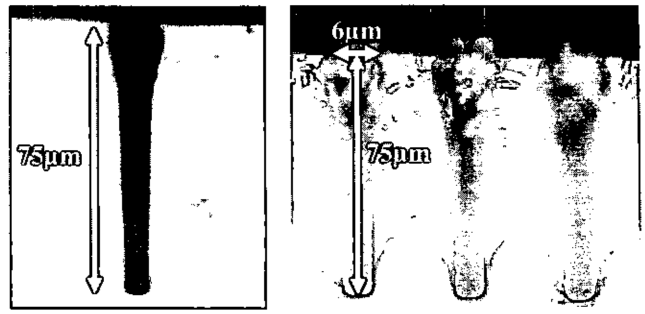


Figure 2: Process Flow.

A fabricated device with a radius of 1 mm is shown in Fig. 4. The radius of the central supporting cylinder is 100 μm. The spiral channel ends at a 100 μm long, 6 μm wide pointing tip, and the rotation angle can be optically recorded from 5 degree/division indicators surrounding the device. Because the device is still open to environmental pressure, a photoresist drop is dispensed over the central cylinder and dried to seal the channel at a controllable pressure. At the current phase of development, the device is sealed at 1 atm as the gauge reference.



(a) (b)

Figure 3: Process images taken by an optical microscope: (a) Etched trench; (b) Parylene-sealed channel.

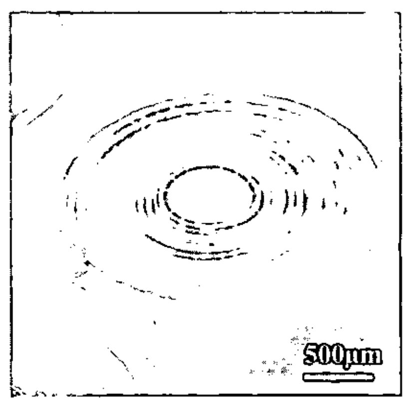


Figure 4: SEM Image of fabricated device.

Process Issues

Ideally, the undercut surrounding the etched trenches (Fig. 2.b) should be isotropic. The physical motion of the reactive ions in plasma, however, leads the SF_6 plasma to first create a "mushroom-like" profile [6] at the bottom of trenches. As the etching time increases, the trench sidewalls are etched in a "vase-like" profile (Fig. 3.a) instead of a uniform one. This phenomenon is more obvious in higher aspect-ratio trenches. In order to create a better profile for greater pressure responses of the spiral channel, a modified DRIE recipe needs to be explored.

Another issue is that the released spirals are vulnerable to outside variation, such as fluid flow, vibration, and electrostatic attraction. These environmental changes can cause the spiral turns to move sideways to contact each other or to unwind out of plane. This is because of the insufficient stiffness of spiral channel. As a result, the fabricated devices should be handled carefully during testing. The vertical and radial rigidity of the channel, therefore, has to be improved with a more robust structural design or with additional supporting structures.

4. Testing and Discussion

Testing Setup

The testing setup illustrated in Fig. 5 is modified from previous work in our group [7]. A system consisting of an N_2 gas cylinder, a particle filter, an Airtrol R-800-60 pressure regulator, and two needle valves is used to regulate the pressure. One needle valve releases the applied pressure after each measurement. This system is connected to a closed chamber to provide different positive-applied pressures. The cap of the chamber is transparent to facilitate external optical observation. A device with a 10-turn spiral is placed inside the chamber and tested (Fig. 6). When a pressure difference is applied between the outside and the inside of the channel, the pointing tip starts to rotate. This behavior is monitored through a stereoscope with 20x magnification and a mounted CCD camera to capture the image. Along with the optical readout, an OMEGA PCL100-30 pressure calibrator is also used to measure the real-time numerical pressure. These two readouts are analyzed to characterize the performance of the device.

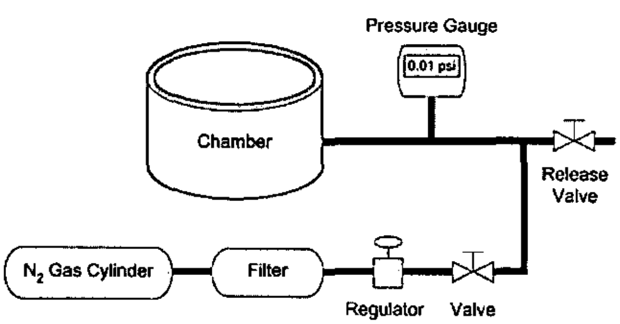


Figure 5: Testing Setup.

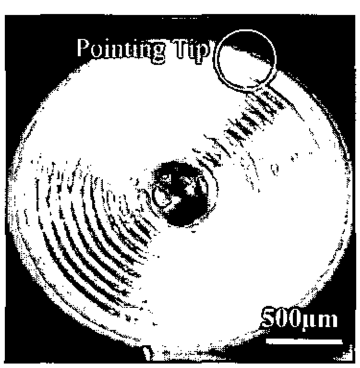
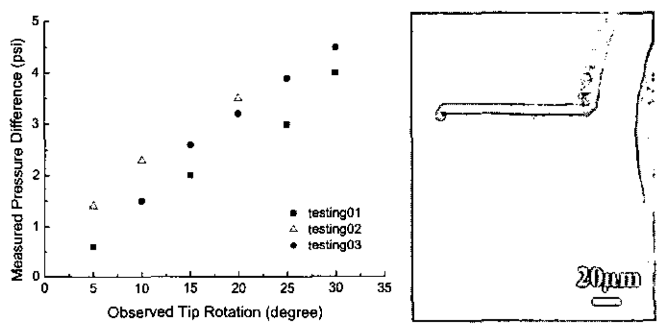


Figure 6: Stereoscope image of device with a 10-turn spiral.

Results and Discussion

The device has been tested in various media (*e.g.* air, IPA, and water) to accomplish feasibility and performance testing. For air, the pressure-rotation relationship is plotted in Fig. 7.a. It was found that, although the tip rotation increases when the pressure difference increases, and their relationship can be fitted well to a linear curve, a continuous pointing-tip rotation can not be achieved with continuous pressure variation. Instead, a discrete-stepping rotation is observed. This is probably because the spiral is lying on the XeF_2-roughened substrate (Fig. 7.b), which induces non-uniform Coulomb friction or stiction that hinders tip rotation. Possibly, when the spiral is released, some attractive forces or thin-film residual stresses in the parylene layer force the downward bending of the spiral channel until the tip is in contact with the substrate. This out-of-plane deformation can be prevented by increasing the vertical rigidity of the channel structure. But, because sensitivity and repeatability are degraded by this behavior, future devices have to be improved for use in an air environment.



(a) (b)

Figure 7: Testing in air: (a) Pressure-driven tip rotation plot. The rotation behavior shows discrete-stepping; (b) SEM image of the pointing tip lying on the substrate.

Nevertheless, further testing the device shows that the adhesion/stiction problems can be avoided in liquids. For example, isopropyl alcohol (IPA) was the first liquid used for pressure testing. The resulting pressure-rotation relationship is plotted in Fig. 8, and remains a linear response. Under this condition, tip rotation is continuous with pressure changes, which means that the stiction between the spiral channel and the substrate is eliminated. The sensitivity in IPA is also improved from that in air. In the pressure range of 6 psi, the measured sensitivity has an average of 0.22 degree/mmHg, with ± 9% variation in specific rotation angles.

The device is also tested in water, which is most comparable to the saline medium of interest in IOP sensing applications. When first immersed in water, the device is not functional because the hydrophobic parylene surface induces formation of bubbles on the surface of device. Thus, when the pressure is above a certain value, some bubbles

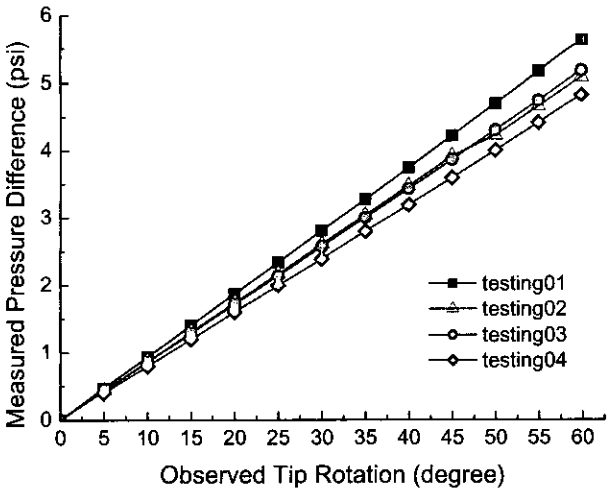


Figure 8: The pressure-driven tip rotation plot for the device tested in IPA.

break and cause serious deformation of the spiral because of the high surface tension of the water. This problem was solved by appropriate surface treatment in oxygen plasma [8]. The spiral can be modified to be more hydrophilic, which reduces bubbling and enables use of the device in water. With the treatment, the device becomes promising for aqueous environments. For example, a pressure-rotation plot of the device is shown in Fig. 9. The measured sensitivity is 0.13 degree/mmHg with ± 15% variation. Currently, more work is focused on improving the sensitivity and reliability of the device.

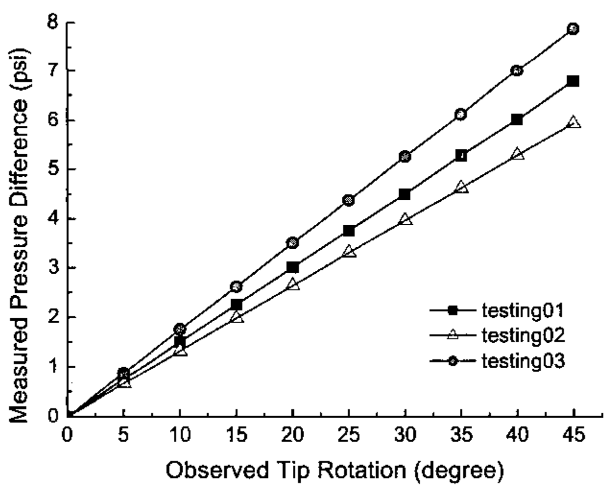


Figure 9: The pressure-driven tip rotation plot for the device tested in water.

5. CONCLUSION

A micromachined intraocular pressure sensor has been successfully fabricated. The passive pressure-driven rotation in a high-aspect-ratio spiral tube facilitates a direct and convenient *in situ* optical measurement of IOP. Experimental results for 10-turn spiral devices have been demonstrated. Different testing media have been used to verify the efficacy of the device in different environments. In IPA and water, the device can realize continuous pressure measurement, but each device has to be individually calibrated for accuracy and precision. By improving the channel structure and increasing the number of turns in the spiral, the pressure response can be greatly enhanced. A more robust supporting structure is also needed for more reliable long-term monitoring of intraocular pressure.

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