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Unpowered spiral-tube parylene pressure sensor for intraocular pressure sensing

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Abstract

This paper presents the first biocompatible, unpowered, micromachined pressure sensor for intraocular pressure (IOP) sensing. This device is designed for implantation in the eye so that IOP can be faithfully measured externally. It features a parylene-based high-aspect-ratio spiral-tube structure fabricated using a buried-channel process. This passive sensor requires no power from other physical (i.e. electrical and/or magnetic) domains and registers pressure variations by changes of a mechanical in-plane spiral rotation that can be gauged by direct and convenient optical observation. The fabricated device has been tested in various media, and a 1 mm-radius device with a 10-turn spiral has successfully demonstrated continuous spiral rotation when immersed in liquids, with 0.22°/mmHg sensitivity in isopropyl alcohol (IPA) and 0.13°/mmHg sensitivity in water. This pressure sensing technology is proposed as a convenient method to monitor in situ IOP in glaucoma patients and to facilitate treatment and scientific study of the disease.

Keywords: High aspect-ratio; Intraocular pressure; Parylene; Pressure sensor; Spiral tube

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) [1]. 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 the disease.

Current tonometry techniques involve indirect measurement of IOP [1,2]. The non-contact optical applanation tomometer used in common practice, however, has difficulty in achieving faithful IOP readout because of the nature of outside measurement, and cannot be deployed for regular monitoring of pressure fluctuations and treatment progress. Many microelectromechanical systems (MEMS) pressure sensor designs have been developed [3] because the small scale of MEMS devices can be specifically applied to IOP sensing [2,4]. 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, other major difficulties include power consumption and biocompatibility issues. To realize faithful IOP measurement from inside the eye, a new sensing paradigm is proposed. It includes a passive, biocompatible, micromachined pressure sensor. With appropriate securing/anchoring mechanisms, with or without sutures [5], this sensor will be implanted on the iris under the cornea (an overview of ocular anatomy is given in Fig. 1 [6]). This placement enables IOP changes to be measured using standard optical equipment, 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

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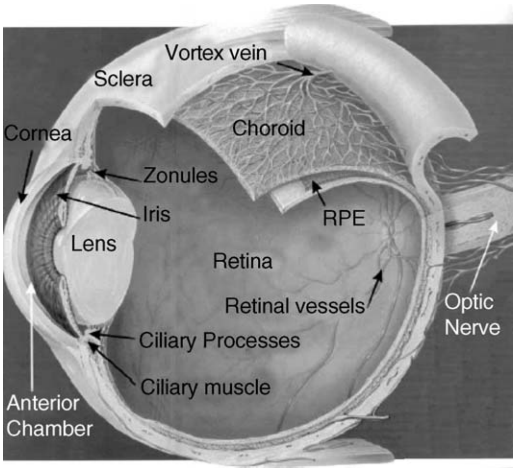

Fig. 1. Overview of ocular anatomy [6]. The pressure sensor is designed for implantation on the iris so as to be visible under external optical magnification.

methodology can be used to carefully monitor and control a patient's glaucoma.

2. Device design

The concept of the device shown in Fig. 2 is based on a Bourdon tube [7]. 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 this specific 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 can be amplified by increasing the number of coiled turns. In addition, a channel structure with thinner walls and a higher aspect-ratio profile is more sensitive to environmental pressure changes. These design factors must be considered to achieve high-pressure sensitivity of the device.

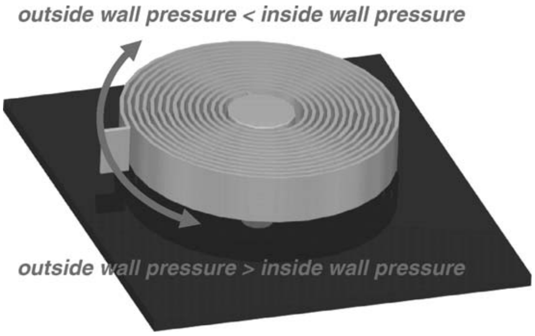

Fig. 2. Device concept. An environmental pressure change is indicated by the rotation of the pointing tip. Note that the spiral tube is essentially a high-aspect-ratio thin-walled channel.

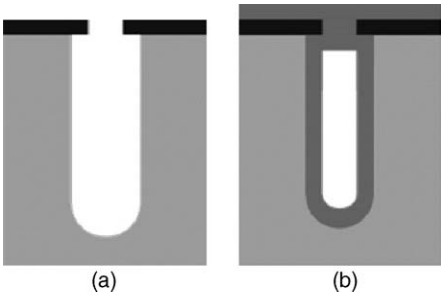

Fig. 3. Illustration of the buried channel process: (a) high-aspect-ratio trench with sidewall undercut; (b) sealed channel after parylene deposition.

Parylene C (poly-para-xylylene C) is selected as the structural material because of its desirable properties such as high flexibility (Young modulus ~3 GPa), chemical inertness, and biocompatibility [8]. Moreover, parylene is compatible with microfabrication technology and can be deposited as a pinhole-free conformal coating at room temperature. It has been broadly used in microfluidic and bioMEMS devices, such as integrated mass flow controllers [9], on-chip electrochemical pumping systems [10], miniaturized high-performance liquid chromatography (HPLC) systems [11,12], and biocompatible neuron cages [13]. Recently, the implementation of a micromachined high-aspect-ratio parylene structure has been successfully demonstrated [14]. In this work, another high-aspect-ratio thin-walled channel structure is developed [15] based on a buried-channel process [16]. By using single-layer parylene deposition bulk-etched trenches are uniformly coated. The top overhang is sealed while the trench beneath is not, which creates a hollow channel as illustrated in Fig. 3. This structure is utilized as the main frame of our spiral-tube device.

3. Device fabrication

3.1. Process flow

The fabrication process shown in Fig. 4 begins with 0.5 μm wet oxidation on a standard 4-inch silicon wafer. After patterning the oxide, a conventional Bosch process in a PlasmaTherm™ DRIE system (Unaxis Inc., St. Petersburg, FL) is used to make high-aspect-ratio trenches. SF_6 plasma etching is then performed to isotropically undercut the silicon surrounding the trenches. Fig. 5a shows the 75-μm-deep, 6-μm-wide trenches with 2.5 μm sidewall undercut that can be created using the above process. Before parylene coating, a short C_4F_8 deposition in DRIE system is performed to intentionally degrade the adhesion between the silicon and the parylene. Subsequently, a 5-μm-thick parylene C layer is deposited in a Cookson Electronics™ PDS system (Specialty Coating Systems Inc., Indianapolis, IN). This highly-conformal coating simultaneously seals the trenches to form the spiral channel, the pointing tip, surrounding indicators that gauge the degree of tip rotation, and a parylene "web" structure at the center that supports the spiral channel. The parylene is then patterned as in Fig. 5b by using oxygen