

BLACK-SILICON AS A MULTIFUNCTIONAL MATERIAL FOR MEDICAL IMPLANTS: FIRST DEMONSTRATED USE IN IN-VIVO INTRAOCULAR PRESSURE SENSING

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Novelty/ Progress Claims

We report the first *in-vivo* demonstration of using multifunctional black silicon (b-Si) as a medical technology for implants. Integrating b-Si on a microscale implantable intraocular pressure (IOP) sensor has significantly improved the sensor's signal-to-noise ratio by suppressing the background noise and enabled the use of a common clinical ophthalmic microscope for IOP measurements on fully awake rabbits at a 12-cm readout distance, which presently stands as the world record. Furthermore, b-Si showed a remarkable antifouling property during a 6-month *in-vivo* study. It minimized tissue proliferation and encapsulation on the ocular implant, promising much improved long-term implant reliability.

Background/ State of the Art

Recently, we demonstrated continuous *in-vivo* IOP monitoring in rabbits under anesthesia using a microscale sensor implant and a microscope readout system (Fig.1) [1]. Our sensor implant is a hermetically sealed microscale optical cavity made of a top deformable transparent silicon-nitride membrane and a bottom reflective Si surface, separated by a 4- μm air gap. The pressure change deflects the membrane and changes the cavity's gap size and optical resonance, which is optically detected to obtain the corresponding IOP (Fig.2).

To make this technology more readily accessible to clinicians, adaptation of easy-to-use, well-established systems such as ubiquitous ophthalmic microscopes for IOP readout is highly desired. Furthermore, minimizing biofouling on the implant is necessary for long-term reliable signal transduction.

Increasing the readout distance, however, expands the measurement field and increases background noises, dominated by the highly reflective inactive region of the sensor. In addition, approximately 10% of implanted sensors show a sign of tissue growth on polished silicon surfaces.

Description of the New Method or System

We chose b-Si as a multifunctional biomaterial for our sensor implant to overcome the engineering challenges [2]. B-Si, a textured silicon (Si) surface with micro- and nanoscale high aspect-ratio

topology, is known to possess highly useful surface properties such as anti-reflectivity and anti-biofouling and is utilized in a myriad of applications [3].

To suppress the background noise from the passive (i.e. not involved in transduction) regions of the sensor, anti-reflective b-Si was grown over these regions (Fig.1). Using a mixed-mode plasma etch, we developed a novel room-temperature b-Si process that did not require an expensive cryogenic setup or a time-consuming cooling process and seamlessly integrated it into the existing sensor-fabrication process. In addition, by adding a spectrometer and CCD camera, we prepared an ophthalmic microscope with a 12-cm working distance as a readout system. Then, two sensors, b-Si-textured and untextured, were implanted inside rabbit eyes and observed over 6 months (Fig.3). We retrieved the sensors after 6 months and examined them using immunofluorescence microscopy to evaluate tissue growth/biofouling.

Experimental Results

We first compared the *in-vivo* optical performance of the b-Si-textured and untextured sensors and found that b-Si effectively suppressed undesired optical background bias of the sensor by over a factor of 10 (Fig.4a). This resulted in 75% decrease in peak-to-peak variation from ± 8 mmHg to ± 2 mmHg (Fig.4b); 70% decrease in root-mean-square error (RMSE) from 1.96 mmHg to 0.58 mmHg (Fig.4c,d); and much lower standard deviation of 0.48 mmHg compared to 1.45 mmHg of the Tonovet measurements (Fig.5a). Additionally, the b-Si-textured sensor maintained SNR consistently over 10 dB for 3 months (Fig.5b).

To investigate the extent of surface fouling and its influence on the sensor reliability, we retrieved the implanted b-Si-textured and untextured sensors after 6 months and performed confocal immunofluorescence microscopy to determine cell and tissue viability at the time of extraction. We found that using b-Si curbed tissue growth on the active sensing region by 92% (Fig.6). In addition, several instances of inflammation were present in the case of the untextured sensor while none was observed on the b-Si-textured sensor (Fig.7), promising much improved long-term device reliability.

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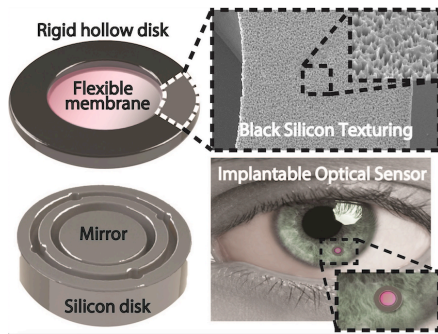


Figure 1. Illustration of the IOP sensor and its use: the two parts integrated multifunctional b-Si.

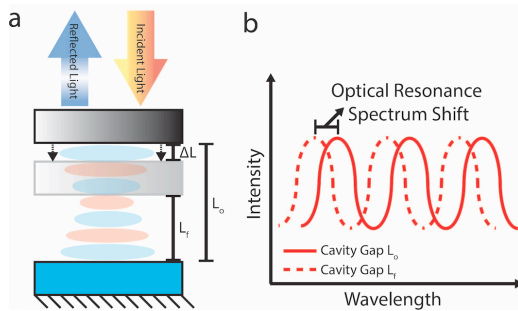


Figure 2. Sensor operating principle: (a) pressure-sensitive optomechanical cavity and (b) optical resonance shift due to the air gap change.

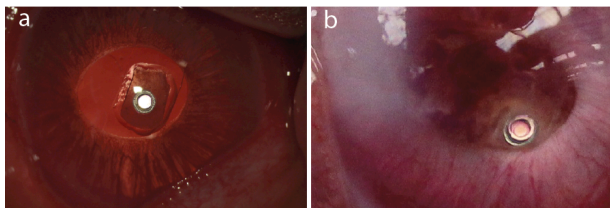


Figure 3. (a) The b-Si-textured and (b) untextured sensors implanted inside the eyes of living rabbits.

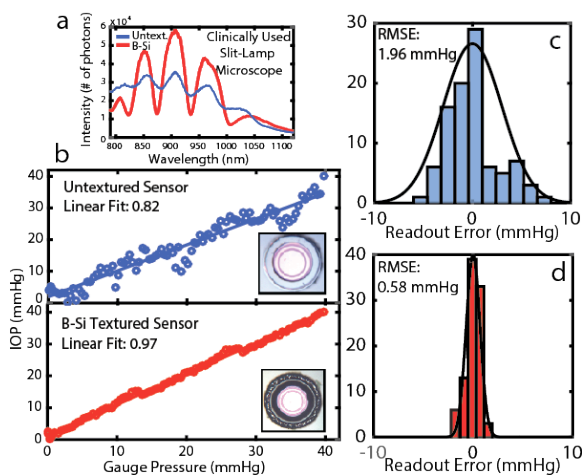


Figure 4. (a) Superior benchtop performance of b-Si-textured sensor due to suppression of background noise when tested using an ophthalmic microscope. (b) a higher correlation factor in case of the b-Si sensor (the lower plot). Insets show optical images of the untextured and b-Si sensors. (c, d) lower RMSE in b-Si textured sensor.

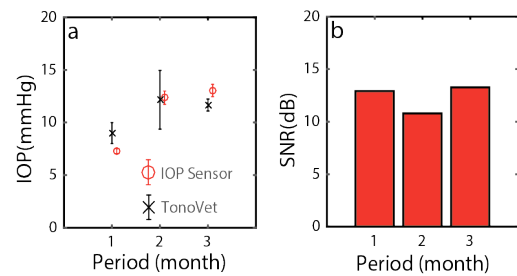


Figure 5. (a) Superior in-vivo performance of the b-Si sensor over a Tonovet. (b) the b-Si sensor's SNR: consistently over 10 dB for 3 months.

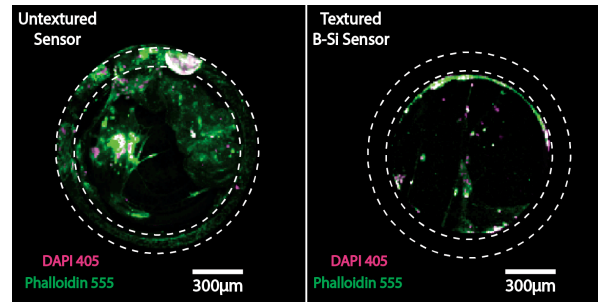


Figure 6. Extent of biofouling after 6 months on the two sensors (immunofluorescence microscopy, DAPI 405: nucleus marker and Phalloidin 555: f-actin marker).

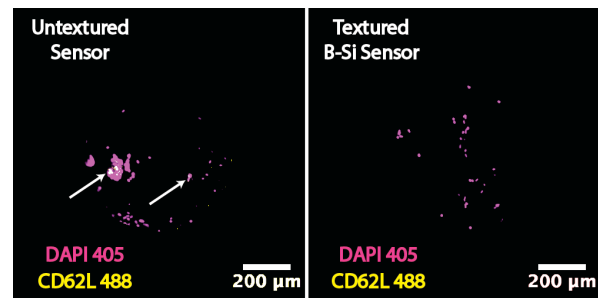


Figure 7. Inflammation (white arrows) observed on the untextured sensor while no inflammation observed on the b-Si sensor. (CD62L 488: l-selectin inflammation marker)

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