A batch fabricated capacitive pressure sensor with an integrated Guyton capsule for interstitial fluid pressure measurement

Teimour Maleki
Birck Nanotechnology Center, Purdue University

Benjamin Fogle
Birck Nanotechnology Center, Purdue University

Babak Ziaie
Birck Nanotechnology Center, Purdue University, bziaie@purdue.edu

Follow this and additional works at: http://docs.lib.purdue.edu/nanopub

Part of the Nanoscience and Nanotechnology Commons

Maleki, Teimour; Fogle, Benjamin; and Ziaie, Babak, "A batch fabricated capacitive pressure sensor with an integrated Guyton capsule for interstitial fluid pressure measurement" (2011). Birck and NCN Publications. Paper 1021.
http://dx.doi.org/10.1088/0960-1317/21/5/054005
A batch fabricated capacitive pressure sensor with an integrated Guyton capsule for interstitial fluid pressure measurement

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2011 J. Micromech. Microeng. 21 054005
(http://iopscience.iop.org/0960-1317/21/5/054005)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 128.46.221.64
The article was downloaded on 26/07/2013 at 19:09

Please note that terms and conditions apply.
A batch fabricated capacitive pressure sensor with an integrated Guyton capsule for interstitial fluid pressure measurement

Teimour Maleki¹,², Benjamin Fogle¹,² and Babak Ziaie¹,²,³

¹ School of Electrical and Computer Engineering, Purdue University, W Lafayette, IN, USA
² Birck Nanotechnology Center, Purdue University, W Lafayette, IN, USA
³ Weldon School of Biomedical Engineering, Purdue University, W Lafayette, IN, USA

Received 1 November 2010, in final form 7 February 2011
Published 28 April 2011
Online at stacks.iop.org/JMM/21/054005

Abstract
In this paper, we present the design, fabrication and test of a batch fabricated capacitive pressure sensor with an integrated Guyton capsule for interstitial fluid pressure measurement. The sensor is composed of 12 μm thick single crystalline silicon membrane and a 3 μm gap, hermetically sealed through silicon–glass anodic bonding. A novel batch scale method for creating electrical feed-throughs inside the sealed capacitor chamber is developed. The Guyton capsule consists of an array of 10 μm diameter access holes etched onto a silicon back-plate separated from the silicon sensing membrane by a gap of 5 μm. The presence of the Guyton capsule (i.e. plates with access holes plus the gap separating them from the sensing membrane) allows for the ingress of interstitial fluid inside the 5 μm gap following the implantation, thus, providing an accurate measurement of interstitial fluid pressure. The fabricated sensor is 3 × 2 × 0.42 mm³ in dimensions and has a maximum sensitivity of 10 fF mmHg⁻¹.

(Some figures in this article are in colour only in the electronic version)

1. Introduction
Interstitial fluid pressure (IFP) is an important physiological parameter determining the exchange of fluid between capillary beds and inter-cellular space [1]. In addition, it plays an important role in several pathologies such as lung edema [2], renal disorders [3], hydrocephalus [4] and compartmental syndrome [5]. In oncology, IFP is an important clinical parameter indicating the accessibility of many solid tumors to therapeutic agents [6–9]. This is in light of the fact that higher levels of IFP in tumors impede the efficient delivery of drugs. In addition to chemotherapy, radiation therapy can also benefit from lowering the IFP by increasing the oxygen partial pressure in hypoxic tumor regions.

Although several methods for lowering interstitial pressure using anti-angiogenic agents have been developed [10, 11], to date no method for continuous monitoring of IFP has been reported. The ability to measure IFP using an implantable micro-transponder would provide valuable data for evaluating various pharmacological agents used to lower the IFP. In addition, by measuring the IFP, one can tailor the administration of IFP lowering drugs to optimize their efficacy (e.g., administration of the chemotherapeutic agent when the IFP is reduced). All IFP measurement methods reported so far, including the gold standard capillary servo-null technique, rely on inserting an externally connected fragile transducer into the tumor and measuring the pressure in acute settings [12, 13].

In 1963, Guyton introduced a perforated capsule for chronic measurement of IFP [14]. In his pioneering experiments, Guyton implanted celluloid and methacrylate capsules (in one case the capsule was 2.5 cm in length and 0.8 cm in diameter having 100 holes of 1 mm each) in subcutaneous tissues of dogs. After 2–3 weeks the capsules were filled with in-growing tissue and interstitial fluids (the air inside the capsule is absorbed and replaced by interstitial fluid within 4–7 days). Subsequent insertion of a fine needle into the capsule provided a direct access to the interstitial fluid for chronic measurements of IFP. These measurements for the first time proved the existence of negative IFP in certain tissues, thus changing the way physiologists had envisioned fluid transport across capillary beds.
Recently, MEMS technology has provided a unique opportunity to fabricate miniature pressure sensors that can be implanted in tight anatomical locations (e.g., inside the eye, brain and vascular system) [15–19]. In general, micromachined pressure sensors can be divided into two categories, i.e. piezoresistive and capacitive. Capacitive pressure sensors have distinct advantages compared to their piezoresistive counterparts making them an attractive alternative for many medical applications. These include higher sensitivity, smaller temperature dependence and lower power consumption [20–23]. However, they require a more complicated fabrication process due to the requirement for a hermetic lead transfer to a sealed cavity. Several processes (both batch scale and die level) with varying complexities have been reported to allow electrical feed-through without compromising the hermeticity [24–27].

In this paper, we present a simple fabrication process for a Guyton capsule embedded capacitive pressure sensor. The sensor fabrication relies on a combination of (1) modified lift-off process for planarized gold feed-through interconnects, (2) anodic bonding of an SOI and a glass wafer, (3) gold electroplating to fill the feed-through holes, and (4) dry etching of silicon handle substrate combined with an isotropic SiO₂ wet etch to create the Guyton capsule. The developed sensor can be used in conjunction with a wireless telemetry system for chronic (long-term) measurement of IFP. The presence of the Guyton capsule will also be effective in isolating the sensing membrane from the deleterious effects of cell and fibrous tissue encapsulation, thus reducing the long-term drift of the sensor.

2. Sensor structure and design

Figure 1(a) shows the schematic of the pressure sensor. It is composed of a 300 μm thick glass wafer (Hoya SD-2) acting as the fixed plate of the capacitor, a 12 μm thick single crystalline silicon layer as the flexible diaphragm, a sealed cavity with a 3 μm gap, and a Guyton capsule formed by an array of 10 × 10 × 100 μm³ access holes separated from the sensing membrane by a 5 μm gap (in this paper, we designate the gap separating the access holes from the sensing membrane as the Guyton chamber while reserving the term Guyton capsule for the gap and the access holes taken together as a unit). The membrane’s overall dimensions are 1 × 1 × 0.012 mm³. Figure 1(b) shows a cross-sectional view clearly demonstrating various layers and structures.

Although many groups have reported on FEM simulations for capacitive pressure sensors, most of these attempts only consider the membrane deflection due to the ambient pressure gradient. In our simulations, two additional elements were added in an attempt to improve the accuracy. The first was the thermal stresses generated during anodic bonding due to the mismatches between the thermal expansion coefficients of silicon and glass. The second was the effects of air trapped inside the sealed cavity, since the anodic bonding used to form the cavity is done at atmospheric pressure rather than vacuum.

A finite element simulation of the sensor was done using the COMSOL Multiphysics™ software package to obtain a 3D model of the electric field in the deformed geometry, defined by the Moving Mesh (ALE) application mode. Figure 2(a) shows the middle point deflection versus ambient pressure. As can be seen, even at atmospheric pressure, the membrane is deflected by 1.68 μm. Capacitance versus pressure is depicted in figure 2(b), while figure 2(c) shows the pressure sensor sensitivity versus applied pressure.

3. Fabrication process

Figure 3 shows a schematic of the fabrication process. It starts with an SOI wafer (a 350 μm thick handle layer, a 5 μm thick buried oxide and a 15 μm thick device layer). To reduce the stray capacitance, the device layer was selected to be highly resistive (>1000 Ω cm). A 3 μm deep rectangle was etched in the device layer using reactive ion etching (RIE) to act as the sensing capacitor gap, figure 3(a). The desired depth was achieved by controlling the RIE process parameters such as time, power and gas flow rate. Two holes (50 μm wide and 15 μm deep) were then created in the device layer by DRIE to be used as access contacts for the feed-throughs, figure 3(b). Next, the buried oxide at the contact locations was removed using wet HF (resulting in 20 μm undercuts), figure 3(c). This intentional undercut plays an important role in the subsequent
Electroplating step. Afterward, 300 nm silicon-rich LPCVD nitride layer was deposited to cover the entire wafer to act as the passivation layer for the metal electrodes, figure 3(d). This step was followed by a deposition and lift-off of 10 nm/100 nm Cr/Au electrode layer on both SOI (figure 3(e)) and glass wafer (figure 3(f)). A modified lift-off process in which a shallow (100 nm) recess was etched onto the nitride prior to the metal deposition was used to achieve a highly planarized (non-uniformity < 60 nm) surface which is crucial for the quality of the anodic bonding process.

Glass and SOI wafers were then cleaned and anodically bonded (\( T = 400 \, ^\circ C, \, V = 1000 \, V \)), figure 3(g). After bonding, the handle layer was thinned down to \( \sim 100 \, \mu m \) using TMAH (20%, 90 °C). Then DRIE was used to create the backside access holes and open the contact area, figure 3(h). A short (3 s) dip in an ultrasonic bath was used to break the nitride residue on top of the feed-through access holes. Next a 10 nm/100 nm Cr/Au seed layer was sputtered, followed by 15 \( \mu m \) gold electroplating to fill the feed-throughs, figure 3(i). Finally, a 15 min HF etch was performed to undercut the buried oxide layer and establish the Guyton capsule (i.e. the access holes and the gap separating them from the sensing membrane, interstitial fluid will accumulate inside this space following implantation), figure 3(j).

Figure 4 shows an optical micrograph of the fabricated sensor showing the contact regions and access holes (magnified image).

The above-mentioned fabrication process contained several critical steps designed to ensure a hermetic sealed cavity with electrical feed-throughs. These included: (1) a modified lift-off process to ensure a highly planar surface following the Cr/Au deposition, figure 5(a) shows AFM image of the boundary between the Cr/Au interconnect and nitride layer; (2) long zigzag interconnect traces, figure 5(b);
Figure 3. Fabrication process for a Guyton-capsule-embedded pressure sensor.

Figure 4. Optical micrograph of a fabricated device.

(3) gold–gold contact ring around the feed-through holes, figure 5(c); and (4) electroplated gold at the feed-through holes, figure 5(d). Leakage in this process is mostly through the nanochannels formed along the interconnect traces. It has been suggested that if the step height along the feed-through is less than 60 nm, the pressure formed during anodic bonding will close this channel, resulting in a hermetic seal [28]. The AFM in figure 5(a) shows a step height of <50 nm (except an initial edge of 140 nm formed at the sidewall of the photoresist which is deformed by the high pressure of the anodic bonding). Furthermore, a long and narrow zigzag line decreases the leakage probability. The gold–gold contact ring and subsequent through-hole electroplating further blocks the remaining leakage path.

4. Results and discussion

For successful Guyton capsule access-holes fabrication, DRIE parameters (pressure, coil and bias power, and gas flow) had to be adjusted carefully. As the access holes are deep and narrow, silicon etch may stop before reaching the buried oxide layer, figure 6(a); or be slower in the access holes compared to the
contact areas due to the lag effect, figures 6(b) and 3(g) and (h). SEM picture of the final device with completely open access holes is depicted in figure 6(c). The device is cleaved such that various layers and structures are visible (see the magnified image).

Following the fabrication process, the sensors were tested for leakage and no base-line drift was observed over a period of several weeks of storage in the nitrogen box. The sensors were then tested for sensitivity, figure 7. At low pressures (below 830 mmHg) capacitance change versus pressure was linear (a sensitivity of 10 fF mmHg$^{-1}$), as expected theoretically. At higher pressures (above 830 mmHg), the gap was almost closed and a sharp increase in capacitance was observed. At 870 mmHg, the gap was completely closed and two electrodes were shorted out. No passivation layer was used in these sensors; however, a thin PECVD nitride passivation layer can be added after electrode formation to prevent shortage at higher pressures and allow the sensor to be used also in the touch-mode, increasing the dynamic range. Nevertheless, the maximum of the previously reported interstitial pressure is 820 mmHg [7], which remains in the linear region of the pressure sensor’s operation. In the case of rare ultrahigh interstitial pressure, the nonlinearity in the output curve can be compensated electronically using the calibration curve.
Figure 6. SEM of a cleaved device showing (a) etch stoppage in the access holes, (b) slower etch rate in the access holes and (c) successful access holes fabrication. Magnified image shows different layers and structures.

Figure 7. Experimental results showing capacitance versus pressure.
5. Conclusions

In conclusion, we reported on the first micromachined capacitive pressure sensor that incorporates an integrated Guyton capsule. Such a capsule is essential in accurate measurement of IFP which in turn will provide critical information for a variety of pathological conditions such as indicating a ‘window of opportunity’ for the administration of chemotherapeutic agents following a reduction of the IFP. The fabrication process incorporates several steps to ensure a hermetic seal. In addition, the presence of the Guyton capsule will isolate the sensing membrane from the deleterious effects of cell and fibrous tissue encapsulation, thus reducing the long-term drift of the sensor. Experimental measurement of the sensor’s sensitivity closely matches the simulation; however, the measured base capacitance is higher than the predicted value. This higher base capacitance is due to the long interconnection traces and contact pads on the silicon substrate. Future efforts will be focused on integration of the sensor into a wireless telemetry system for chronic measurement of IFP.

Acknowledgments

We would like to thank the staff of Birck Nanotechnology Center at Purdue University for their help and assistance. Funding for this work was provided by the National Institute of Health grant 1R21EB007256.

References

[10] Lin M I and Sessa W C 2004 Antiangiogenic therapy: creating a unique ‘window’ of opportunity Cancer Cell 6 529–31