A BIOCOMPATIBLE GLASS-ENCAPSULATED TRIAXIAL FORCE SENSOR FOR IMPLANTABLE TACTILE SENSING APPLICATIONS

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ABSTRACT

This paper reports a microfabricated triaxial capacitive force sensor. The sensor is fully encapsulated with inert and biocompatible glass (fused silica) material. The sensor comprises two glass plates, on which four capacitors are located. The sensor is intended for subdermal implantation in fingertips and palms and providing tactile sensing capabilities for patients with paralyzed hands. Additional electronic components, such as passives and IC chips, can also be integrated with the sensor in a hermetic glass package to achieve an implantable tactile sensing system. Through attachment to a human palm, the sensor has been shown to respond appropriately to typical hand actions, such as squeezing or picking up a bottle.

KEYWORDS

Triaxial force sensor, tactile sensing, capacitive sensing, fused silica, hermetical package, biocompatible package, fusion bonding.

INTRODUCTION

Tactile force sensors play a pivotal role in restoring hand function after paralysis. With the help of tactile sensors in conjunction with an appropriate strategy, such as brain-machine interface (BMI) technology, tactile signals can be translated into electrical signals by the sensors and conveyed to a brain stimulator that activates a somatosensory area, resulting in a sense of touch.

Numerous efforts have been made for the development of tactile force sensors [1]–[7]. Many previously reported tactile sensors are based on polymer materials and built on flexible substrates, such as polyethylene terephthalate (PET), polydimethylsiloxane (PDMS), and flexible printed circuit boards, and are intended primarily for wearable scenarios.

For neuroprosthetic systems aimed at reanimating a patient's own paralyzed hand, implantable sensors in the palm or fingertip may be preferred since the donning of wearables can be a challenge for these patients. However, implantable sensors generally present greater challenges in fabrication and material selection. Hermeticity and biocompatibility are basic requirements to ensure long-term reliable operation within the human body. Implantable sensors usually require such a hermetic environment, which can protect their internal sensing components from the harsh environment of the human body. The biocompatibility of implantable sensors or sensor packages should be considered to ensure they do not elicit adverse reactions in the body. Also, in the case of implantable tactile sensors, a small form factor is required since the sensors are intended for implantation in palms and fingertips.

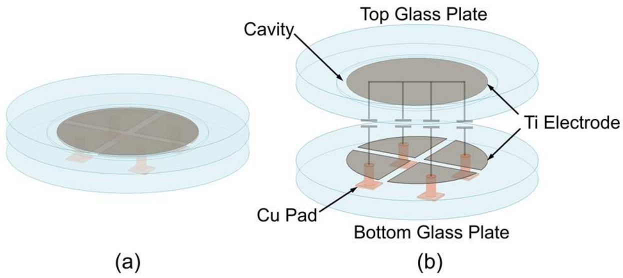

Figure 1: (a) glass-encapsulated triaxial force sensor and (b) its exploded view.

Over the past several decades development of implantable biomedical systems, materials, including Titanium (Ti), alumina, and fused silica, have been approved to satisfy the long-term hermicity and biocompatibility requirements of implantable sensors. For instance, a fused-silica based pressure sensor has been clinically used for permanent implantation in the distal pulmonary artery to monitor the pulmonary artery (PA) pressure [8]–[10].

Previously a silica-based uniaxial implantable tactile sensor was demonstrated [7]. Compared with that previous work, in which the sensor could only sense normal forces, the sensor reported here can sense forces along three different axes, including shear forces and normal force. Consequently, the triaxial force sensor offers a better tactile sensing capability, bringing it closer to mimicking the functionality of a real hand. Also, a simpler and optimized fabrication process for this class of sensors over the previous work has been developed in this paper.

GLASS-ENCAPSULATED FORCE SENSOR

Sensor Design

Fig. 1 shows the proposed glass-encapsulated triaxial force sensor. The sensor comprises two fused silica plates. There is an etched cavity on the backside of the top plate. A circular-shaped Ti electrode is lithographically formed within the cavity as a floating electrode. On the bottom plate, there are four quarter-circular-shaped Ti electrodes. Each Ti electrode is connected to a copper (Cu) pad on the other side of bottom plate by means of a through-glass via. The Cu pads are used as the outputs for sensing signals. The circular-shaped Ti electrode on the top plate, along with the four quarter-circular-shaped Ti electrodes on the bottom plates and the air gap created by the top plate's cavity, collectively form four capacitors. The top glass plate is relatively thin and will deform when force is applied. This results in variations in the gap distance and corresponding changes in capacitance. The direction and

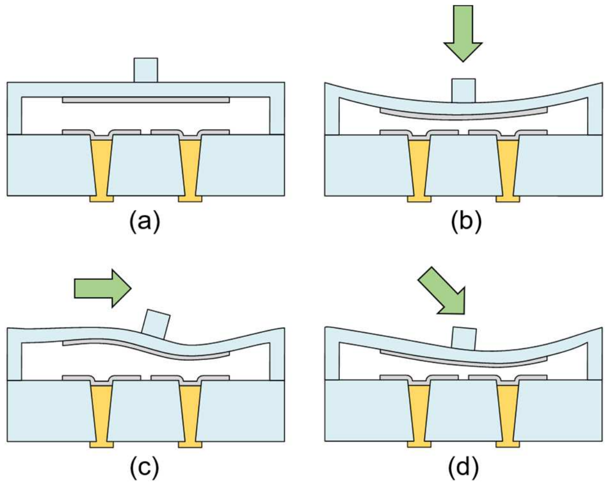

Figure 2: Sensor operation principle. (a) no force; (b) applying a normal force; (c) applying a shear force; (d) applying a force at an angle.

magnitude of the applied force are reflected in the capacitance change of the four capacitors. Therefore, triaxial force sensing is achieved.

A more detailed illustration of the sensor operation principle is shown in Fig. 2. A glass pillar can be placed at the center of the top plate to increase the sensing sensitivity to shear force. Fig. 2(a) shows the sensor without applying a force. When a normal force is applied (Fig. 2(b)), the gap between top and bottom plate is reduced. Therefore, the capacitance of the four capacitors is increased simultaneously. When a shear force is applied (Fig. 2(c)), the air gap on the left side is increased, while the air gap on the right side is reduced. This leads to an increase in the capacitance of the two right-side capacitors and a decrease for the capacitance of the other two capacitors on the left side. In the case of a force is applied at an angle to the sensor (Fig. 2(c)), the capacitance of all the four capacitors increases, and the capacitance increase of the right-side two capacitors are more significant.

To realize a complete tactile sensing system, additional electronic components can be placed on the Cu pad side of the bottom plate. These electronic components will be connected to the Cu pads of the sensor by wire bonding or flip-chip bonding. A supplementary fused silica plate with a deep cavity is used as a lid to encapsulate these electronic components. The three plates are bonded together using a laser-assisted fusion bonding technology [11]. In this way, the triaxial force sensor and other electronic components are fully encapsulated with glass and have a hermetic environment.

Sensor Fabrication

The sensor comprises multiple plates, as detailed previously. Each plate is individually fabricated using a 4-inch fused silica wafer with a different thickness. Fig. 3 shows the major fabrication steps of the glass-encapsulated force sensor, encompassing individual plate fabrication through final assembly.

The top plate fabrication starts with a 4-inch 200-µm-thick fused silica wafer. A cavity is first formed using reactive ion etching (RIE) with a photoresist mask.

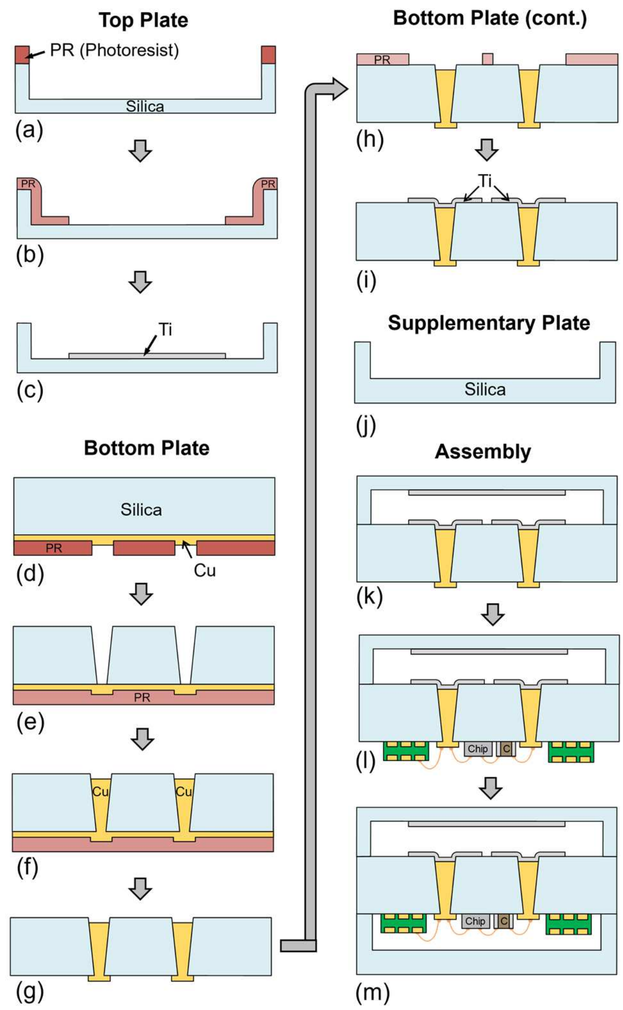

Figure 3: Major fabrication steps of the triaxial force sensor. Top plate fabrication: (a) cavity etching; (b) photoresist patterning; (c). Ti electrode formed by lift-off. Bottom plate fabrication: (d) backside Cu pad formation; (e) through-glass via laser drilling; (f) via filling by Cu electrodeposition; (g) seed layer removal; (h) photoresist patterning; (i) Ti electrode formed by lift-off. Supplementary plate fabrication: (j) cavity laser ablation. Assembly: (k) top and bottom plates bonding; (l) electronic components attachment and wire bonding; (m) fusion bonding of multiple glass plates.

The depth of the cavity is approximately 4.0 µm. Subsequently, a layer of photoresist is spray-coated and patterned to define the Ti electrodes. Following this, a 200-nm-thick Ti layer is sputtered. The Ti electrodes on the top plate are formed using a lift-off approach.

The bottom plate fabrication starts with a 4-inch 500-µm-thick fused silica wafer. A seed layer of Ti and Cu is sputtered on the backside of the wafer. Photoresist is spin-coated and patterned into a mold in the shape of the Cu pads. The photoresist acts as an electroplating mask, and Cu electroplating is carried out to form the Cu pads. After the electroplating, another photoresist layer is coated to protect the Cu pads without removal of the seed layer. Subsequently, through-glass-vias are drilled using an excimer laser. The vias have a square shape with a size of 200 µm × 200 µm. The power and the number of pulses of the excimer laser are precisely controlled to avoid damage to the Cu pads during drilling. A second round Cu electroplating is performed to fill the vias with Cu. The plating process stops just before the Cu reaches the wafer surface. Subsequent to the electroplating, the seed layer is removed using a commercial copper etchant (Copper Etch BTP, Transene), followed by a hydrofluoric acid (HF) etch. The Ti electrodes on the bottom plate are then formed using the lift-off approach, identical to the method employed for the top plate.

To fabricate the supplementary plate, a 4-inch 1-mm-thick fused silica wafer is used. A cavity with a depth of 700 µm is formed using a CO_2 laser. During the CO_2 laser ablation, a portion of the vaporized fused silica is redeposited around the cavities on the wafer surface, resulting in the formation of small silica bumps. These small bumps may cause problems for the subsequent fusion bonding. To address this issue, a HF dip is performed to remove the silica bumps after the laser ablation.

After fabricating the silica plates, the top and bottom plate are fusion bonded together. Precise alignment of the top and bottom wafer can be achieved using a wafer bonder. In our experiment, the top and bottom wafers are diced into 20 mm × 20 mm chips. Subsequently, two chips from the top and bottom wafers are carefully aligned. A CO_2-laser-based fusion bonding process is performed to simultaneously cut the circular-shaped sensor from the chip stack and hermetically fuse the edges of the top and bottom layers comprising the sensor. [11]. Because of the extremely low thermal conductivity of fused silica, this fusion can occur without temperature-induced damage to the internal components.

For the fabrication of a complete tactile sensing system comprising a lower plate and encapsulated electronics, the top and bottom fused silica plate are aligned and temporarily bonded first. Subsequently, electronic components, including an integrated circuit (IC) chip and passive elements, are attached to the backside of the force sensor. Following the chip and passives attachment, the supplementary plate is positioned as a lid as shown in Fig. 3(m). Finally, the CO_2 laser is used to cut the sensor from the chip stack and simultaneously fusion bond the three silica plates together.

RESULTS AND DISSCUSSION

A glass-encapsulated triaxial force sensor is fabricated as shown in Fig. 4, using the developed fabrication process. The sensor has a diameter of approximately 6.8 mm and a total thickness of 0.7 mm. A relatively large gap of 1.6 mm between the sensor edge and the circular-shaped Ti electrode is reserved to prevent the Ti electrodes and Cu pads from being affected by the heat generated during the CO_2 fusion bonding process. This gap distance can be further reduced if a CO_2 laser with a smaller beam size is adopted.

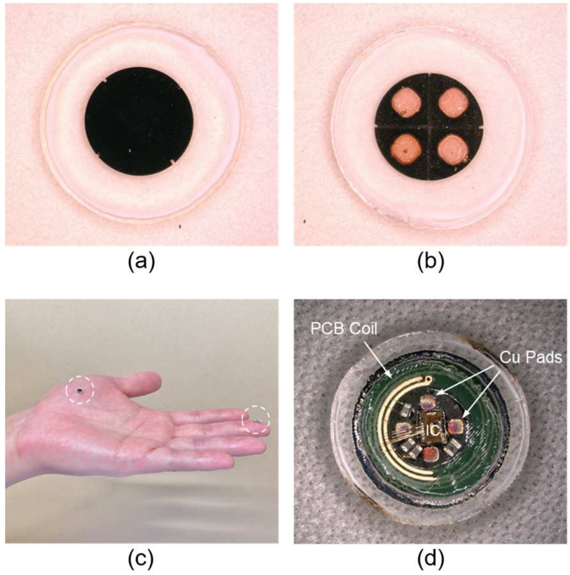

Figure 4: Fabricated triaxial force sensor. (a) top view; (b) bottom view; (c) sensors on a hand; (d) sensor integrated with other electronic components for a wireless tactile sensing system.

To demonstrate the efficacy of proposed fabrication process for tactile sensing system applications, a triaxial force sensor integrated with additional electronic components is also fabricated. An IC chip, a printed circuit board (PCB) with a coil on it, and passive components are positioned around the Cu pads on the bottom plate. These components are connected to the Cu pads via bonding wires. With the help of these electronic components, a wireless tactile sensing system can be achieved. The sensor and all the other electronic components are fully encapsulated with glass. As shown in Fig. 4(d), after the fusion bonding, no damage to the bonding wires, the IC

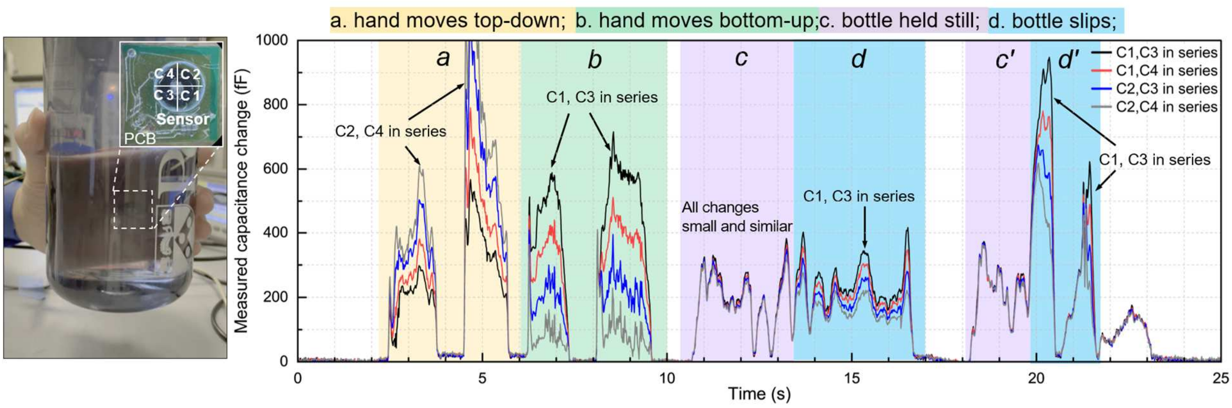

Figure 5: Measured capacitance changes of the triaxial force sensor on a palm when holding a bottle.

chip, or the sensor is observed. Sensor testing shows that full wireless operation of the sensor system is achieved.

To facilitate access to various sensor functions during further testing, the sensor module comprising the upper two silica plates is soldered on a test PCB. On that PCB, there is an IC chip, a trace coil, and passives, which are used to acquire and process the sensor's outputs. The processed data is transferred wirelessly using the trace coil. Another coil in wristband form is used to receive the data. The received data is read out on an oscilloscope. Detailed information about the tactile sensor test platform and the read-out circuit design can be found in [12]. Fig. 5 shows a preliminary test result of the fabricated triaxial force sensor on a palm when holding a bottle. During the measurement, a glass pillar is glued at the center of the front side of the sensor to increase the sensing sensitivity to shear force. Four data sets of capacitance changes are collected. The corresponding positions of the four capacitors on the tactile sensor are shown in the upper left area of Fig. 5. Since the bottle is held by the hand tightly at all times, a constant normal force component is applied to the sensor regardless of the different hand actions. Therefore, the measured capacitance changes are consistently positive. During the hand's movement along the bottle from top to bottom (Fig. 5(a)), the top two capacitors (C2 and C4) undergo the most compression. Therefore, the capacitance increase of the two capacitors is largest. Conversely, when the hand moves along the bottle from bottom to top (Fig. 5(b)), the bottom two capacitors (C1 and C3) experience the greatest compression, leading to the most significant increase in capacitance. When the bottle is held stationary (Fig. 5(c)), only a normal force is applied on the sensor. The four capacitors are compressed equally, resulting in nearly identical capacitance changes. The case of bottle slipping downward mirrors the hand's action of rubbing the bottle from bottom to top. Two slip cases are tested: a small slip (Fig. 5(d)) and a large slip (Fig. 5(d')). In both cases, the sensor responses are similar to that the hand moving from bottom to top, with a large slip showing a larger magnitude response. These measurement results clearly show that the capacitance of the fabricated triaxial sensor varies in correspondence with forces associated with different typical hand actions.

CONCLUSION

This paper presents a triaxial force sensor, which is fabricated on fused silica wafers and fully encapsulated within the biocompatible silica material. When attaching the sensor to a human palm, the sensor shows appropriate responses to different hand actions. The sensor is promising for implantable tactile sensing applications.

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