SOG Fabrication of Bulk Micromachined and Bonded Capacitive Inertial Sensor Structures

Vijayekumar Rajaraman, Gabriel Craciun, Heng Yang, Emile van der Drift and Patrick James French

Abstract—**This paper reports on a silicon-on-glass fabrication process for in-plane capacitive MEMS inertial sensors with a high aspect ratio. A 2-mask process was developed by application of Bosch DRIE process and two wafer bonding techniques, namely, anodic bonding and adhesive wafer bonding with BCB. Microstructure definition is done by deep RIE of bulk silicon into an etched cavity that is then lined with an oxide passivation layer before being bonded face-down to a glass substrate. Finally, the movable parts of the micro-inertial device are dry-released by maskless plasma thinning of silicon from the backside.**

***Index Terms*—SOG-MEMS, DRIE, wafer bonding, inertial sensor, gyroscope**

I. INTRODUCTION

RECENTLY, there has been an ever-increasing demand and drive for the development of low cost and high performance MEMS inertial sensors for various applications. Bulk micromachining using deep RIE (DRIE) technology enables realization of high performance 3D MEMS inertial sensors with a high aspect ratio (HAR), superior mechanical and thermal properties due to use of single crystal silicon (SCS), a thicker proof mass leading to a higher sensitivity, and a relatively larger output capacitance and smaller chip area. Such inertial sensors are attractive for a multitude of applications in the aerospace, automotive, consumer, defense and medical fields. Bulk micromachined devices, hence, are a good candidate for manufacturing inertial sensors such as accelerometers, gyroscopes, inclinometers, etc.

Capacitive inertial sensing is performed by detecting the deflection of a movable proof mass electrode with respect to one or more fixed electrodes. The proof mass movement introduces a capacitance change either by varying the inter-electrode gap or their contact area depending on the sensor design. Bulk capacitive inertial sensors can be fabricated by micromachining either a bonded silicon substrate or a thick SOI substrate. The latter approach, although straightforward, involves the use of an expensive starting material. On the other hand, the bonded wafer approach is a low cost process involving the use of a bulk silicon wafer bonded to a glass or silicon handling wafer.

This paper reports on a silicon-on-glass (SOG) MEMS process flow, that combines Bosch DRIE process [1] and two wafer bonding techniques, which is suitable for fabricating in-plane capacitive HAR inertial sensors. Both anodic bonding and adhesive bonding with BCB are considered, offering process flexibility. In this process, mechanical patterns are defined by DRIE into a pre-etched cavity that are later oxide-lined and either anodic bonded or BCB bonded to a Pyrex glass substrate. The movable MEMS parts are then dry released from the backside of the silicon wafer by plasma thinning of silicon. The basic structure of a resultant SOG bulk micromachined inertial device is shown in Figure 1.

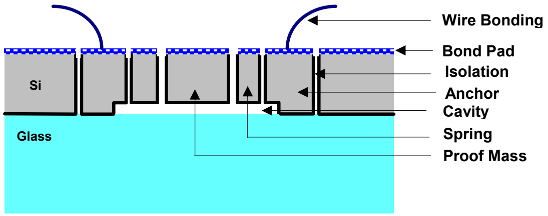


Fig. 1. Cross-sectional representation of a SOG micro-inertial device.

Inertial devices with different structural thicknesses could be fabricated with the proposed process flow. Capacitive MEMS devices will benefit from this SOG MEMS process due to the use of SCS and insulating properties providing low parasitic capacitance that aids in improving the device performance. With some process modifications, the SOG MEMS approach could offer the possibility to integrate z-axis detection electrodes for sensors requiring vertical movement detection. The developed process as such allows integration of the inertial MEMS devices with electronics as a two chip system.

II. FABRICATION PROCEDURE

Previously, the authors of [2] reported a process flow for fabricating bulk inertial devices using cryogenic DRIE process involving cavity etching in silicon, silicon flip-over, anodic bonding of silicon to glass, silicon wafer thinning by mechanical grinding and polishing followed by deep etching of microstructures at cryogenic temperatures. However, the fabrication results were unsuccessful, especially for devices with critical dimensions, due to the difference in thermal

---

V. Rajaraman, G. Craciun and Prof. Dr. P.J. French are with the Electronic Instrumentation Laboratory, Department of Microelectronics, DIMES, Delft University of Technology, The Netherlands (phone: +31-15-27-89177; fax: +31-15-27-85755; e-mail: v.rajaraman@tudelft.nl).

Dr. H. Yang was with the Electronic Instrumentation Laboratory, Dept. of Microelectronics, DIMES, Delft University of Technology, The Netherlands. He is now with the Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai, P.R. China.

Dr. E. van der Drift is with the Nanofacility, Kavli Institute of Nanoscience Delft, Delft University of Technology, The Netherlands.

conduction between glass and silicon during cryogenic etching. It is known that the cryogenic DRIE process suffers from temperature sensitivity [3] and requires continuous flow of liquid nitrogen for cooling of the wafer stage to cryogenic temperatures. Consequently, for successful cryogenic processing homogeneous thermal conduction paths across the entire wafer need to be established, implying that the backside wafer surface must be clean with the wafer preferably consisting of a single substrate material. Hence resultant etch profiles of critical microstructures, on an anodic or adhesive bonded wafer, will strongly be influenced when using cryogenic etching.

To overcome the limitations of the above approach, SOG MEMS inertial sensors were fabricated in a different process scheme using just two masks, illustrated in Figure 2. The Bosch DRIE process was performed at room temperature in AMS-100 ICP DRIE system and the optimized DRIE process parameters are presented in Table I. Recipe A was used for etching microstructures and recipe B was used for plasma thinning of the bulk silicon wafer. For microstructures etching, the silicon etch rate was 2.7 µm min^{-1}, the mask selectivity was 158:1, the lateral underetching was better than 400 nm per side, and an AR as high as 29 was achieved. For silicon wafer thinning, a significantly higher etch rate was used.

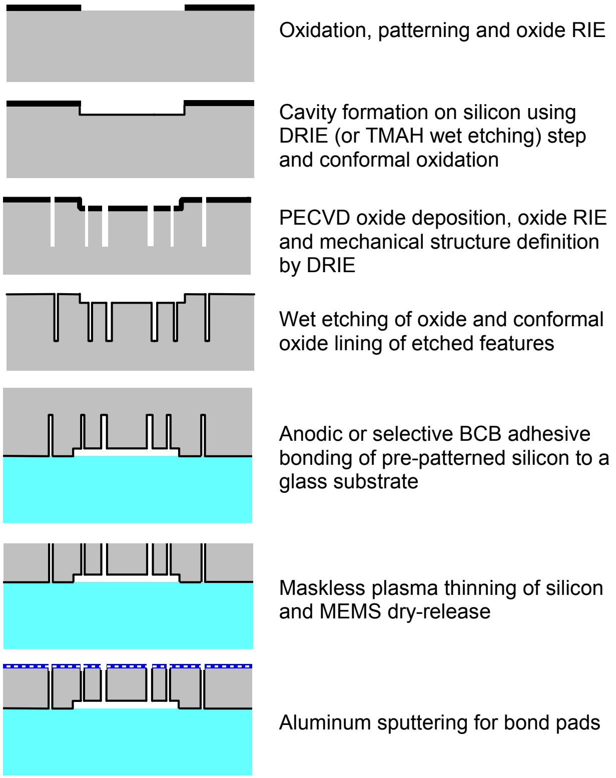


Fig. 2. SOG-MEMS process sequence.

The processing was performed on 100 mm silicon (100) wafers (p-type, low resistivity, 525 µm thick). Low resistivity wafers were used in order to obtain good ohmic contacts. The procedure began with etching a 3 µm deep cavity on silicon wafer that defined the perimeter of the free-standing MEMS parts. The cavity etching could be performed with either a first DRIE step or a 25 wt% TMAH solution at 85°C using thermal oxide as a masking layer. A 2 µm PECVD oxide layer is then deposited on top of a thin conformal oxide layer and patterned. The mechanical microstructure definition is done by a second DRIE step. The residual oxide mask is removed in BHF (1:7) solution and the microstructures are lined with a thin conformal layer of thermal oxide.

TABLE I
BOSCH DRIE PROCESS PARAMETERS

Process Parameter	Recipe A	Recipe B
SF_6 Etch Gas Flow [sccm]	420	200
C_4F_8 Passivation Gas Flow [sccm]	280	70
SF_6 Etch Gas Step Time [sec]	5	7
C_4F_8 Passivation Gas Step Time [sec]	2	3
Plasma Power [Watts]	1500	2000

The silicon wafer is now flipped and bonded to a glass wafer either using anodic bonding or BCB adhesive bonding. Anodic bonding of pre-patterned silicon wafer to a Pyrex glass substrate was performed in EV501 bonding equipment at 440°C and 700V. Selective adhesive bonding was performed using dry-etch BCB (Cyclotene 3022-57) [4] that required a maximum curing temperature of 250°C. When using BCB bonding, also non-sodium containing glass wafers like AF45 could be used. The silicon wafer is then plasma thinned without using any mask, eliminating the need for mechanical wafer thinning and polishing (CMP), and stopping on the oxide lined trench bottom that is RIE etched, dry-releasing the MEMS device. Finally, a very thin layer of aluminum metal is sputtered for bond pads.

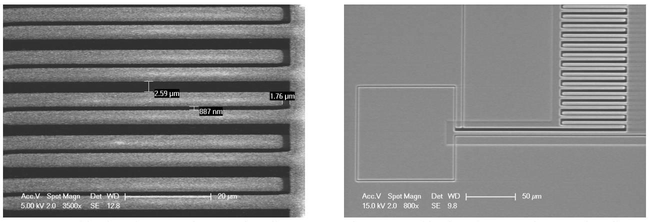
III. RESULTS AND DISCUSSION

A. *Etching of Capacitive Inertial Sensors*

HAR capacitive MEMS inertial sensors such as accelerometers and gyroscopes were fabricated with the SOG-MEMS process.

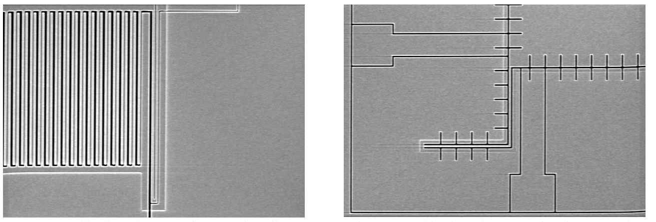
1) *Comb Electrodes and Spring Structures*

In a capacitive MEMS inertial sensor, often microstructures such as comb finger electrodes, folded and unfolded spring structures are used. Such structures were etched using the SOG process and the results are presented in Figure 3.



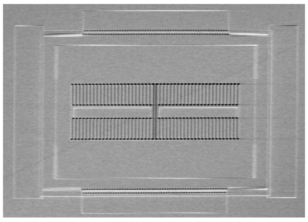
(a) Detailed view of comb finger electrodes of an accelerometer

(b) Detailed view of comb finger electrodes, a straight spring and the anchor of an accelerometer



(c) Detailed view of comb finger electrodes and part of a folded spring of an accelerometer

(d) Detailed view of the spring, electrodes and anchor of a gyroscope



(e) Birds-eye view of a decoupled gyroscope with comb electrodes

Fig. 3. Inertial sensor structures fabricated using the SOG-MEMS process flow.

2) *Vibratory Gyroscope*

A gyroscope, shown in Figure 4, was fabricated in the SOG-MEMS process. The quad-beam vibratory gyroscope structure has a proof mass suspended by four beams capable of movement in the x and y directions. The gyroscope works in a two-dimensional driving mode [5], where the proof mass is driven into vibration in both the driving (x) and sensing (y) directions.

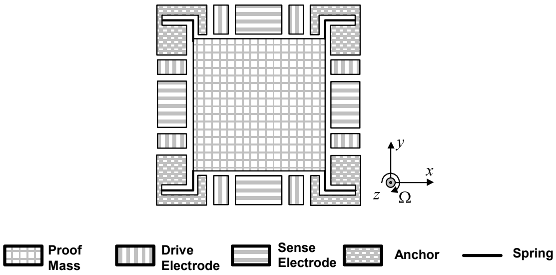


Fig. 4. Schematic of the gyroscope.

The gyroscope employs electrostatic driving and capacitive sensing by means of the movement of proof mass sidewalls against those of the electrodes, with a phase detection scheme featuring a frequency output [2]. The driving vibration in the sensing (y) direction serves as a carrier signal whose phase is modulated by the Coriolis force as a measure of the applied angular rate. As the vibration in the sensing direction is mainly induced by the driving force instead of the Coriolis force, the vibration amplitude is much larger than when driven in just one direction. The driving amplitude in the y direction is designed to be 10 % of that in the x direction in order to increase the sensitivity.

Equal trench gap based design is adopted in the gyroscope design to eliminate the AR dependent etching (ARDE) effect observed in DRIE process. The trench-gap widths were designed to be equal to 6 μm. The symmetrical nature of the device aims at improving the zero stability, linearity and cross-axis sensitivity. A relatively large mass-electrode gap and damping trenches are used in the design to reduce the damping (see Figure 5) and achieve an adequate Q-factor to facilitate device operation in an atmospheric environment. For a device thickness of 50 μm, inclusion of damping trenches resulted in an increase in the computed quality factor (Q) from 43.1 to 62.8 in an atmospheric environment avoiding the necessity for vacuum packaging. The computed characteristics of the designed gyroscope based on [6] are presented in Table II. The thickness of the fabricated devices ranged between 30 and 150 μm. Isolation trenches are etched around the MEMS devices to electrically isolate the different regions.

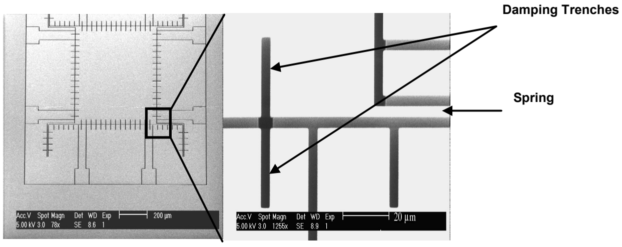
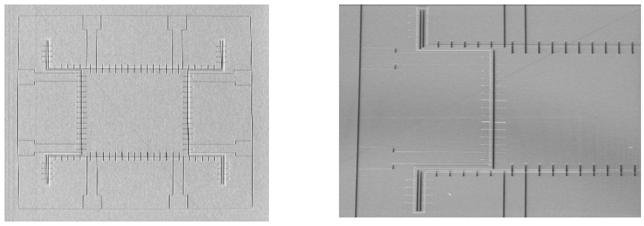


Fig. 5. SEM micrographs showing the top view of the gyroscope structure etched in bulk silicon and an enlarged image of the damping trenches and the spring.

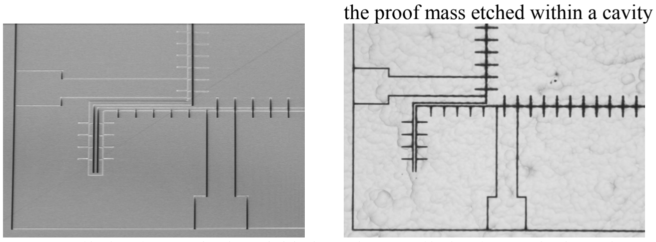
TABLE II
GYROSCOPE PARAMETERS

Mass	74.49 μg
Resonant Frequency	3950 Hz
Quality Factor, Q	152
Sensing Capacitance/Side	3.87×10^{-2} pF
Thermal Noise	$0.02\,^{\circ}/\mathrm{s}/\sqrt{Hz}$
Sensitivity	$12.24 \times 10^{-2}\,^{\circ}/^{\circ}/\mathrm{s}$
Pull-in Voltage, $V_{\text{Pull-in}}$	115 V



(a) Birds-eye view

(b) Close-up view of the springs and the proof mass etched within a cavity



(c) Detailed view of the folded spring, electrodes and proof mass etched within a cavity

(d) Detailed view of the plasma thinned and dry-released spring, electrodes and proof mass

Fig. 6. Gyroscope fabricated using the SOG-MEMS process flow.

Figure 6 shows the images of the fabricated gyroscope structure. Figure 6d shows the detailed view of the plasma thinned, dry-released gyroscope. Plasma thinning of an unpolished wafer surface resulted in a considerable roughness profile. Using a double side polished wafer resulted in a fairly less rough surface. To improve the surface roughness profile, wafer thinning could be performed in three steps. The first step could be used to thin most of the bulk silicon using either plasma etching or wet etching or mechanical lapping and grinding. A subsequent polishing (CMP) step might be used to polish the silicon wafer surface followed by a final plasma etching step to dry-release the inertial MEMS device.

B. *Wafer Bonding*

Both anodic and BCB bonding provided void-free bonding and the bonding results are shown in Figures 7 and 8. The bonded and unbonded regions are clearly indicated. In Figure 8, cavities were first etched on the bottom silicon wafer that was BCB-bonded to a top silicon wafer which was sacrificially etched to reveal the bonding interface.

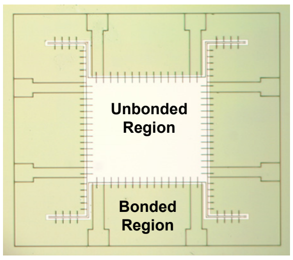


Fig. 7. Micrograph of an anodic bonded quad-beam gyroscope structure viewed through the glass wafer.

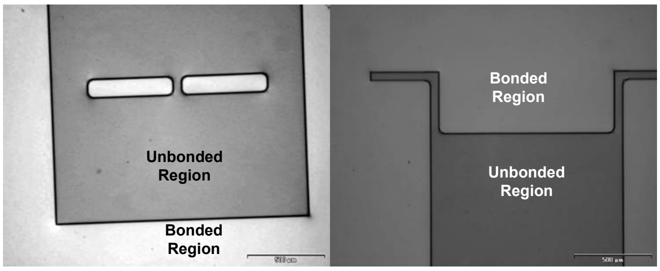


Fig. 8. Micrographs of selective void-free BCB bonding.

IV. CONCLUSION

A SOG-MEMS fabrication process was developed using Bosch DRIE process and two wafer bonding techniques that was applied for the fabrication of in-plane HAR capacitive MEMS inertial sensor structures. A range of microstructures, such as springs, beams, comb electrodes, capacitive structures, suspended structures, etc., often used in the design of MEMS inertial sensors could be fabricated with the developed process. Also other sensors and actuators requiring HAR 3D micromachining could be fabricated using the presented approach.

ACKNOWLEDGMENTS

The authors would like to thank the staff of DIMES Technology Centre and Nanofacility, Delft University of Technology, The Netherlands, for technical support. The author would like to thank the following individuals for many useful technical discussions and assistance during device processing: M. Laros, C. de Boer and H. van Zeijl of DIMES Technology Centre and M. Zuiddam, M. van der Krogt and C.Th.H. Heerkens of Nanofacility. The support of NXP Semiconductors, The Netherlands, in this work is gratefully acknowledged.

REFERENCES

[1] F. Laermer and A. Schilp, “Method of Anisotropically Etching Silicon,” U.S. Patent 5501893, March 26, 1996.

[2] G. Craciun et al, “IC-Compatible Processing of Inertial Sensors Using SF$_6$-O$_2$ Cryogenic Plasma Process,” in *Proc. IEEE Sensors Conf. 2003*, Toronto, Canada, pp. 440-444, 2003.

[3] G. Craciun et al, “Temperature Influence on Etching Deep Holes with SF$_6$/O$_2$ Cryogenic Plasma,” *J. Micromech. Microeng.*, 12, pp. 390–394, 2002.

[4] *Processing Procedures for Dry-Etch CYCLOTENE Advanced Electronics Resins (Dry-Etch BCB)*, Tech Note, The Dow Chemical Company, MI, USA, November 1997.

[5] H. Yang et al, “Two-dimensional Excitation Operation Mode and Phase Detection Scheme for Vibratory Gyroscopes,” *J. Micromech. Microeng.*, 12, pp. 193-197, 2002.

[6] G. Craciun et al, “Implementation of a Quad Beam Gyroscope with On-chip Electronics Integration Compatibility,” in *Proc. Eurosensors XIX*, Barcelona, Spain, 2005.