Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 87 (2014) 991 – 994
Procedia Engineering
www.elsevier.com/locate/procedia

EUROSENSORS 2014, the XXVIII edition of the conference series

Study of the Fabrication Process for a Dual Mass Tuning Fork Gyro

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Abstract

The fabrication process of a dual mass tuning for gyroscope presents many different challenges: the aspect ratio of the sidewalls, the Aspect Ratio Dependent Etch (ARDE) which causes different gaps to be etched in different etching time [1], the stiction during the release of the free structures, the notching effect that occurs with a dielectric etch stop layer [2], the thermal contact during the etch process. In this paper are presented different processes and studies of the etching characteristics in order to avoid or minimize these problems.

Peer-review under responsibility of the scientific committee of Eurosensors 2014
Keywords: MEMS; Gyroscopes; Micromachining; Etching; SOI;

1. Introduction

Micro Electrical Mechanical Systems (MEMS) have a wide range of application among sensors of different kinds, such as mass flow sensors, automotive sensors, RF-switches, controllable micro mirrors, energy harvesters etc. MEMS Gyroscope can be easily miniaturized and integrated in the silicon technologies unlike other kinds of sensors, and they also have low power consumption: this makes them suitable for inertial grade navigation for space application. In order to achieve high sensitivity, the design of the gyro is crucial along with its fabrication process. The studied devices are fabricated on SOI (Silicon On Insulator) wafers of different device layer thicknesses, ranging from 20 to 60 microns. In this way it’s possible to fabricate the device with all its electrodes electrically isolated by simply etching silicon and without depositing any dielectric layer. The vibrating structures are released by etching the bottom layer (handle) of the wafer and the buried oxide (BOX) layer. The device layer is highly doped to provide equipotential and to allow direct bonding without depositing any contact film.

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Peer-review under responsibility of the scientific committee of Eurosensors 2014
doi:10.1016/j.proeng.2014.11.325

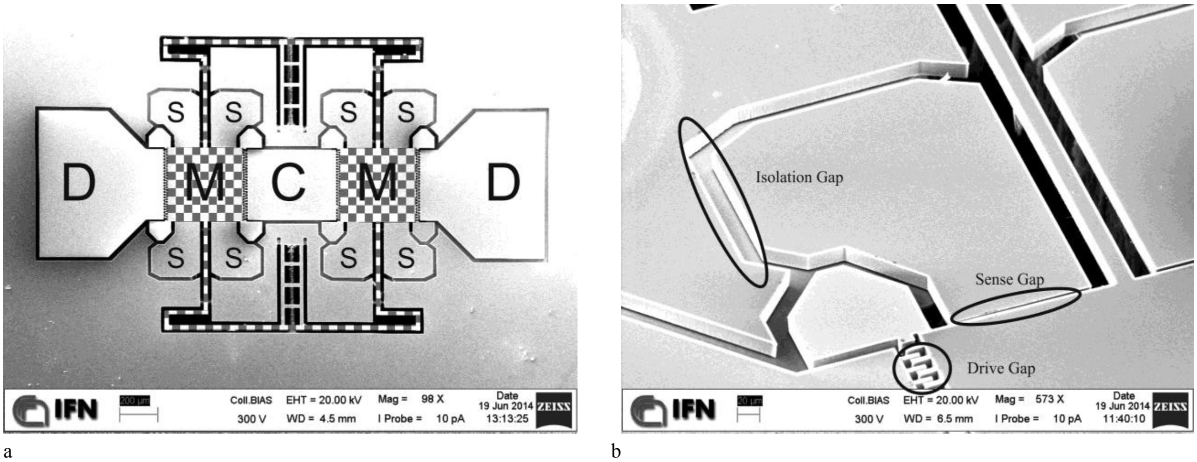


Fig. 1. SEM image (a) of the whole gyro chip; (b) of a detail showing the different gaps etched.

2. Design

2.1. Basic work principle

The design of the studied gyro [3] can be seen in fig. 1a. The working principle of the gyro is the following: the two masses (M) are excited to vibrate (ideally at their resonant frequency) by applying a DC potential on them and an AC potential on the central electrode (C). Due to the Coriolis effect, a part of this vibration (drive), proportional to the rotation rate, will be coupled in the perpendicular axis (sense): this motion is measured by the sense electrodes (S) and represents the output signal of the device. The dual masses serves for vibration (common mode rotation) rejection. Drive electrodes (D) serves for characterization purpose and are not strictly needed for the gyroscope operation. The isolated structures at the four mass corners serves as end position for the mass vibration: they are placed at a distance a little smaller from the mass than the sensing/actuating electrode, so they avoid stitching and snap-down effects.

2.2. Actuation and detection electrodes design

Actuation and detection electrodes have different shape as can be seen in fig. 1b. The actuation electrode is realized by a comb structure (variable area capacitor) and the sensing one by a parallel plate (variable gap capacitor). This grants many advantages, like linear actuation force, high sensing capacitance and the possibility to “tune” the resonant frequency of sense and drive motions to improve sensitivity at the cost of less bandwidth.

3. Microfabrication

3.1. Process flow

The first step is deposition of a mask layer on the front and back side of the wafer. This mask is then pattered with electron beam lithography and photolithography with top/bottom alignment respectively on the device layer and on the handle layer. At this point the device layer is first etched by DRIE (Deep Reactive Ion Etch) to pattern the free structures and the fixed electrodes of the device. Then the handle layer is etched behind the vibrating structures. Finally, the BOX layer is wet etched and so all the structures are released, and the device is ready to be tested.

3.2. Masking

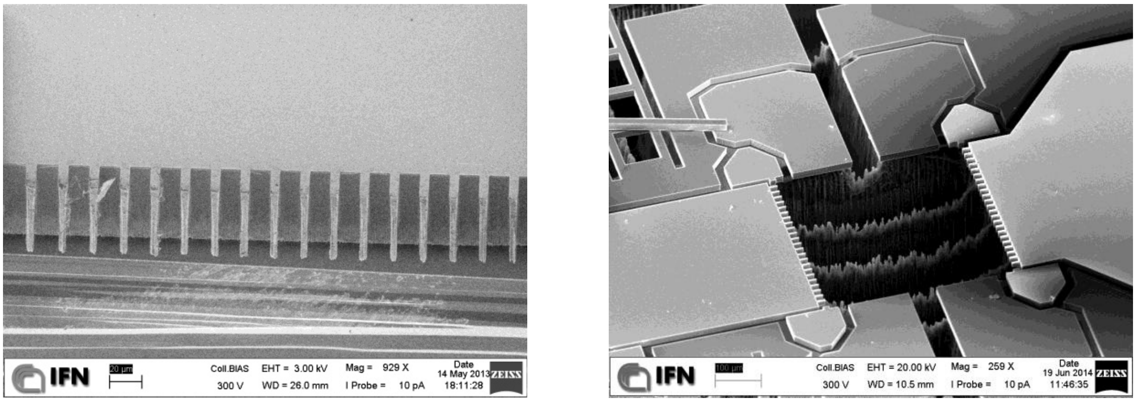
Two different mask materials have been tested, to improve batch quality and fabrication time: silicon dioxide and chromium. The oxide mask is patterned by means of dry etching which grants front/back selectivity (it's possible to pattern one side at a time) and less underetch, but has less selectivity during the etching process. Chromium is far more easier and quicker to deposit and pattern but good adhesion it's very important, otherwise the risk of mask failure is high. This is obtained by sputtering deposition before starting any other process on the wafer.

3.3. Device layer etch

The etching process of the device layer is the most crucial part of the fabrication batch, because every imperfection results in a discrepancy between the expected characteristics (like eigenfrequencies and Q factor) and real ones, and also severe quadrature error may be induced as already explained. So the sidewalls must be as vertical as possible. In order to do so, a Bosh-like process [4] is utilized: a step of silicon attack with SF_6 plasma is alternated with a step of polymerization with C_4F_8. The polymer is deposited isotropically on the surface with a high pressure gas so that the sidewalls in the next low-pressure and more directional attack will be protected. The sample has to be cooled during the attack, otherwise, the polymer fails to deposit on the surface, so the etching proceed isotropically and the underetch is destructive. This process allows high aspect ratio features as can be seen in fig. 2a. This however depends strongly on the geometries etched, as will be further explained.

One more problem that has to be taken into account is the notching effect: this is caused by electric field effects during DRIE etching. When there is an insulating etching stop layer, the ions of the plasma begins to charge its surface and so further ions are deflected and cause a strong lateral etch at the bottom of the device. This particular effect it's problematic in combination with ARDE. Because of their width, sense gaps are etched more slowly than every other trench in the design. This may be a problem for the comb structure of drive electrodes that can be severely damaged at the bottom of the device layer while the etching on sense gaps is not yet finished. A possible solution is to mask larger gaps with resist, in order to start the process only for the gaps that takes longer to be etched. Then after a calculated time depending on the etching rate difference between smaller and larger gap, the resist is removed in acetone and the etching may proceed all over the wafer.

Furthermore it's not possible to see by an optical microscope when the smaller gaps are etched, because of their high aspect ratio (sense trenches are 2 micron wide and up to 60 microns deep). This problem was solved introducing in the wafer some test structures, that allow to determine if the etch is finished by checking the conductivity between two electrodes separated by a gap with the same shape of the device one.



a b

Fig. 2. SEM image of (a) high aspect ratio actuation combs; (b) anchoring points in the handle that are visible under a removed proof mass

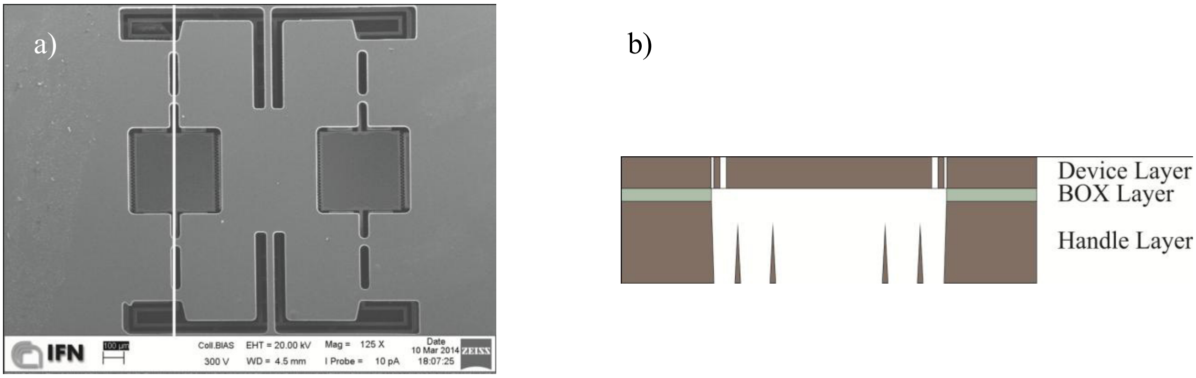


Fig. 3. Anchoring structures in the handle layer. (a) SEM image of the back side of the device; (b) schematic section of the device at the white line in the figure on the left. The scale is not real but functional for the reader's understanding.

3.4. Handle layer etch

The handle layer etching process is slightly different from the device layer, because even if the substrate is the same, the purpose is very different. The main challenge in the back side of the wafer is to release all the vibrating structure while preserving good substrate robustness. As can be seen in figure 1a, the free structures form a closed loop that cannot be etched both on the top and bottom side, otherwise all the structures inside of it would collapse. In this case negative tapering is needed to etch anchor structures in proximity of the device layer (at the bottom of the handle layer), as explained in figure 3. In this case even the notching effect can be useful, should the negative tapering not be enough. A Bosh process is still necessary to achieve solid structures.

Several approaches have been tested to achieve negative tapering. At first the gases pressure in the camber and the total chamber pressures has been increased to reduce directionality of the etching. This slightly increased the negative tapering, but not enough. Another approach with 3-steps Bosh like process has been tested [5] but even in this case the results was not satisfactory. The parameter that changes the most negative tapering is the geometry: larger trench will always exhibit a larger tapering. So slightly changes were made in the handle layer design to take this into account and allow all the vibrating structures to be released.

4. Result and discussion

The pursued study for all the steps of this MEMS gyroscope fabrication process led to different batch of devices, which were bonded in a specific designed PCB interface and their mechanical resonant frequency was found. Several measures was made changing the DC bias, and a shift in the sense eigenfrequency was observed. This denotes that the free system effectively oscillates as designed when an electrostatic force is applied. In a future work the angular rate sensitivity of the gyro will be tested and then further improvements in the fabrication batch will be done.

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