FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

FH Aachen

Fachbereich Maschinenbau und Mechatronik

Study programme Master Mechatronics

Topic 2: Design of an angular rate sensor with the following specifications:

- Bandwidth: DC up to 100Hz
- Measuring range: 600°/s
- Resolution: 0.1°/s
- Integrated test structure to generate a signal corresponding to 100°/s ("Self-test")

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1 Abstract

This paper deals with the conceptual design of an angular rate sensor. At the beginning, the reader is introduced to the basics of the functional principles. The focus is on the spring-mass system, as this is part of the conceptual design. In addition to the introduction to the subject area, various technologies are mentioned that are currently used in industry or are currently being researched. Subsequently, the developed design is presented. This was dimensioned to the requirements of the task using calculations. A simulation strategy was developed to check the calculations. This was to be tested with an appropriate simulation programme. Due to software-related problems, the simulation could not be carried out. Thus, difficulties and limitations are highlighted as a topic. Finally, the manufacturing process was developed. The individual steps that must be carried out during production are presented.

2 Introduction

Angular rate sensors measure the rotational speed with respect to an inertial reference system. Depending on the orientation of the rotation within a system, the rotations are divided into roll, yaw and pitch. In today's world, yaw rate sensors fulfil a variety of tasks and are indispensable for many technological systems. Yaw rate sensors are used in a wide range of applications, from digital cameras, which use such sensors for position stabilization, to space travel, for example, in order to achieve a safe position control of the rocket and thus make modern space travel possible in the first place. Likewise, rate-of-rotation sensors save lives every day by bringing out-of-control vehicles back under control and keeping them under control as a sensory part of the electronic stabilization program (ESP). And in the event that the driver is lost in the confusion of today's road networks, rate-of-rotation sensors can improve the accuracy of vehicle position detection as part of the Global Positioning System. Also in the future, for example in the field of robotics or autonomous driving, rotation rate sensors will be an extremely important component for the further development of these but also other technologies.

The aim of this project was to create a design for an angular rate sensor, including a fabrication process.

3 State of the Art

Micromachined inertial sensors have been subject of intensive research for over two decades. These are gyroscopes for detecting rotational motion and accelerometers for detecting linear motion.

One way to measure angular acceleration is to look at the Coriolis force as a measure of angular acceleration. Micromachined gyroscopes rely on the mechanical coupling of an excited vibration mode into a secondary mode due to the Coriolis acceleration. To measure the input angular velocity, you must consider the magnitude of oscillation in the sense mode. One advantage of a spring-mass based design is that the devices require no rotational parts which would need bearing. Therefore, the design can be relatively easily miniaturized. Since the Coriolis acceleration is proportional to the velocity of the driven mode, it is desirable to make the amplitude and the frequency of the drive oscillation as large as possible. This principle also requires that the frequency and amplitude remain constant since even very small changes can swamp the Coriolis acceleration.

For amplitude control an automatic gain control loop can be used. To ensure frequency stability a phase locked loop can be used.

The coupling from the sense to the drive mode is very weak. Therefore, mechanical amplification is employed. If the resonant frequencies of the drive and sense mode are matched to each other, the coupling is amplified by the Quality-factor Q. To reach this goal the resonance frequencies must match very precisely in the range of <1 Hz. Moreover, this must be maintained over the operating temperature range and other environmental influences. This becomes a challenge due to the tolerances in the mechanical fabrication

process. Due to this issue, active tuning is normally used. The principle relies on applying electrostatic forces on the proof mass. The force acts as a negative spring constant. Even with this active tuning it is still challenging to maintain the tuning over the operating range.

An additional challenge is to avoid the so-called quadrature error. This effect is based on the unavoidable misalignment of the drive mode from the ideal direction. Even small misalignments can cause the sense electronics to saturate. One way to supress the quadrature error at its origin, is applying electrostatic forces to the proof mass.

Novel Approach to Inertial Sensing

Another approach to inertial sensing is now under research at the microelectronics centre of Southampton University. The principle is based on the use of electrostatic levitation. There, a micromachined disk, levitated by electrostatic forces and with no mechanical coupling is

currently under investigation. The disk is engaged by electrodes so that it is levitated at the centre position. The capacity measured between electrodes and the disk is a parameter corresponding to the position of the disk. Since the effective spring constant depends on the applied Voltage, the sensor can be easily adjusted in sensitivity and bandwidth according to the required specification of the use case.
The use of a vibratory rate gyroscope offers several advantages over conventional operating principles. The quadrature error is inherently ruled out by using this principle. Furthermore, there is no need to tune the sense and drive resonant frequencies to achieve a high quality-factor. Since the mechanisms to measure linear and angular motions is decoupled, it could be possible to create a design which measures these quantities in parallel. [1.1]

Immunity to shock and Vibration

An angular rate Senor should provide an accurate signal even under the influence of shocks and vibrations. Especially in the field of automotive applications, there is an increased safety risk if an airbag is triggered due to misinterpreted signals. Thus, the goal is to filter out shocks that lead to this misinterpretation through so-called differential measurement. For this purpose, two structures of the sensor can be used, which work in anti-phase. Thus, non-rotational signals can be filtered. Therefore, the difference between the two sensor signals is used to measure the actual rotation rate. This principle requires a precise manufacturing process of the sensors, so that they ideally represent a copy of each other. This technology is used, for example, by the company *Analog Devices*. [1.0]

4 Design

In this project work, a design based on the Coriolis effect was selected. This is essentially an arrangement of two proof masses produced with surface micromachining which have a comb-like structure and are supported by springs. When these masses are vibrated, they move under the influence of acceleration and rotation. This changes the distance between the comb branches acting as electrodes and a fixed structure, which together form a capacitor, resulting in a measurable change in voltage. Since the oscillating mass also moves under mere acceleration, two of these structures are arranged next to each other and set into opposite oscillation. Under acceleration, the masses move in the same direction. However, as soon as a rotation occurs, the two structures move in opposite directions due to the opposite vibration. These two voltage changes can then be evaluated in a corresponding electronic system and serve as a measure of the rotation speed. In the case of a linear acceleration the two signals add up, whereas in the case of a rotation the two proof masses have signals with opposite signs. From the sum of these two signals the information about the rotation speed can then be evaluated.

Another possibility for improving the measuring range is to keep the Poof mass in the center by means of an appropriate control. The Coriolis force is thus counteracted by applying a voltage. In this case, the measurement for the rotation would be the required voltage. Since the proof mass is held in the center, it is not limited by the restricted range of motion.

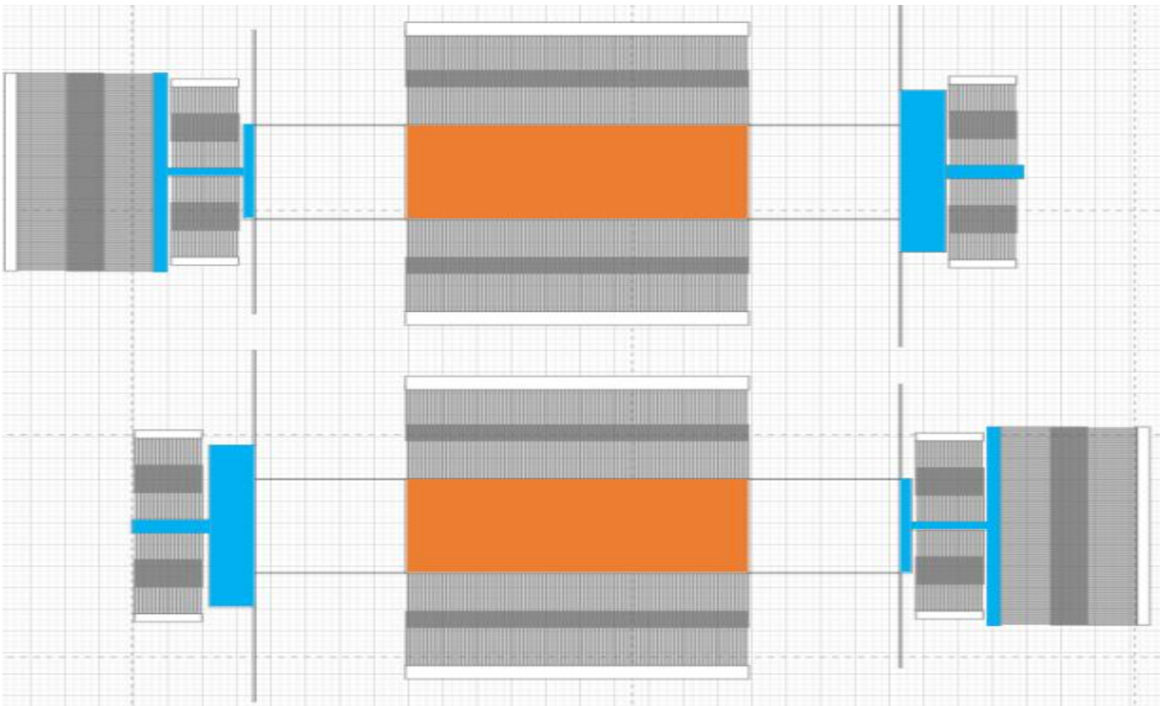


Fig 4.1

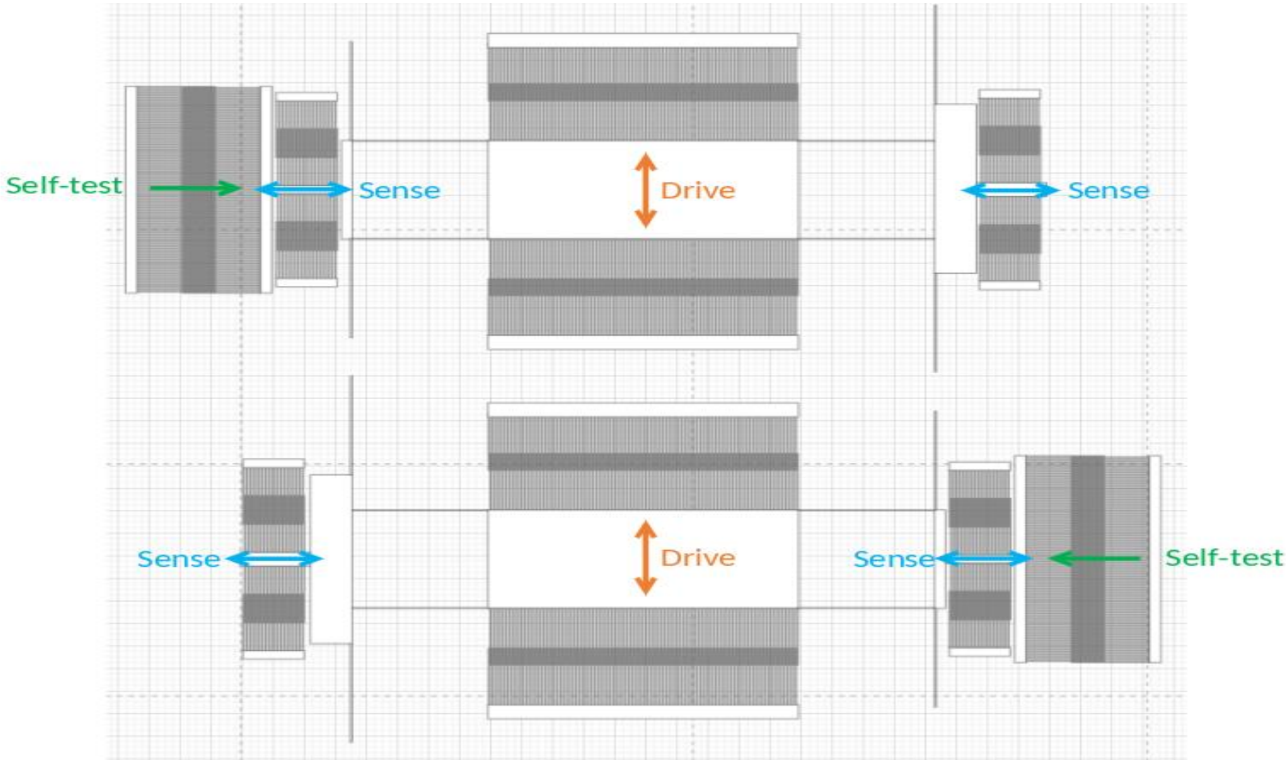


Fig 4.2

Figure 4.1 and 4.2 shows the corresponding number of comb branches and how two accelerometers are used in the design of our angular rate sensor. In the following, a sketch is used to explain the above figures in more detail.

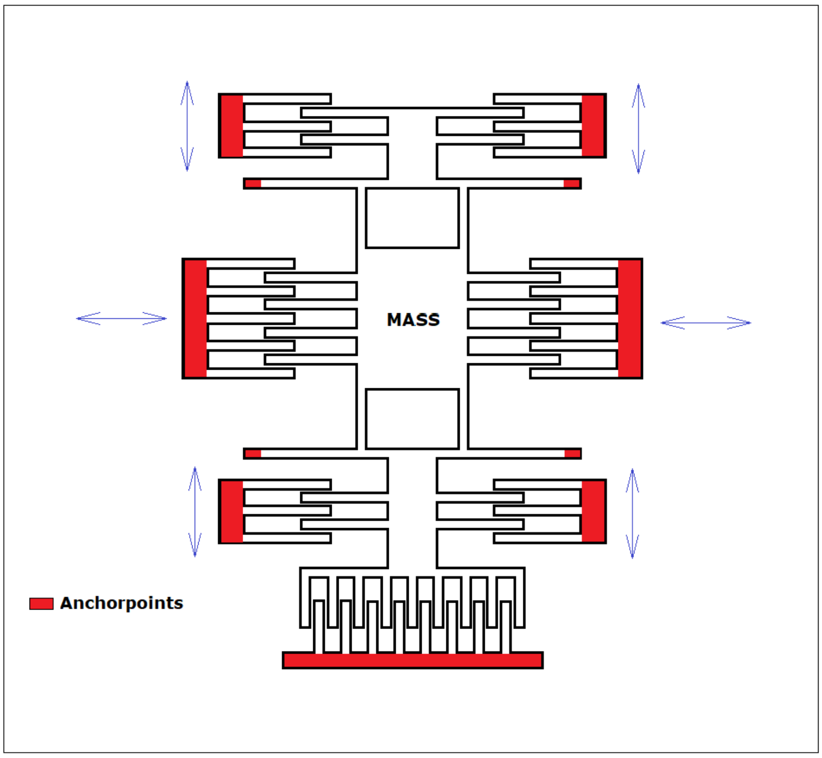


Fig 4.3

Figure 4.3 shows the basic design of one of the two structures. The spring-mounted proof mass in the center is equipped with a large number of comb masts which, together with the firmly anchored combs, form the capacitors. The mass is vibrated by a total of four comb drivers. The two comb structures positioned in the middle can then capacitively detect a longitudinal deflection. The comb drive in the lower middle section is for the so-called "self-test". Here, a deflection of the proof mass can be achieved in order to test the functionality of the comb sensors.

The Coriolis effect

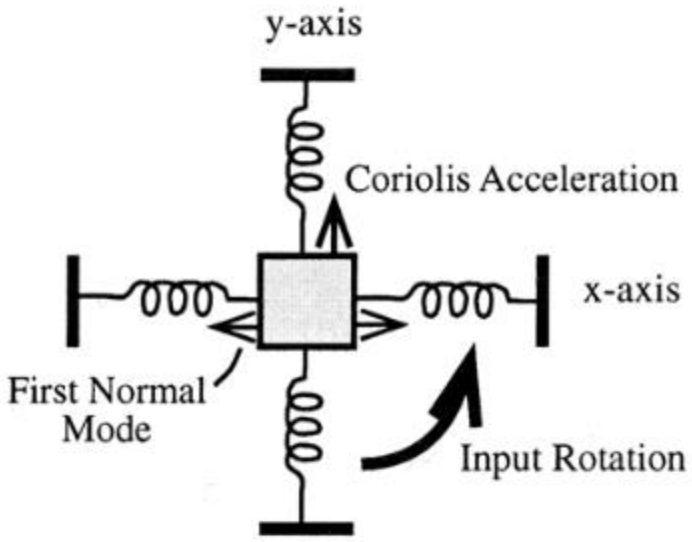


Figure 4.4: Functional principle of an angular rate sensor based on the Coriolis force [4.1]

The Coriolis force is a so-called apparent force. A force seems to act on a linear moving body, as far as the whole system rotates. This phenomenon is responsible, for example, for the jet streams that form. The winds moving from the poles towards the equator are deflected due to the rotation of the earth.

The Coriolis force can be used for sensors insofar as a proof mass is set into oscillation. As soon as an externally acting rotation occurs, this body is deflected as sketched in figure 4.3.

5 Fabrication process

For the fabrication process, PolyMUMPS process is used. "The PolyMUMPs process is a three-layer polysilicon surface micromachining process derived from work performed at the Berkeley Sensors and Actuators Center (BSAC) at the University of California in the late 80's and early 90's" [4.1].
In this process, Crystalline Silicon process is used as the substrate. Polysilicon is used as Silicon nitride is used as electrical insulation between the structure and the substrate. Silicon dioxide layer is used as the sacrificial layer.

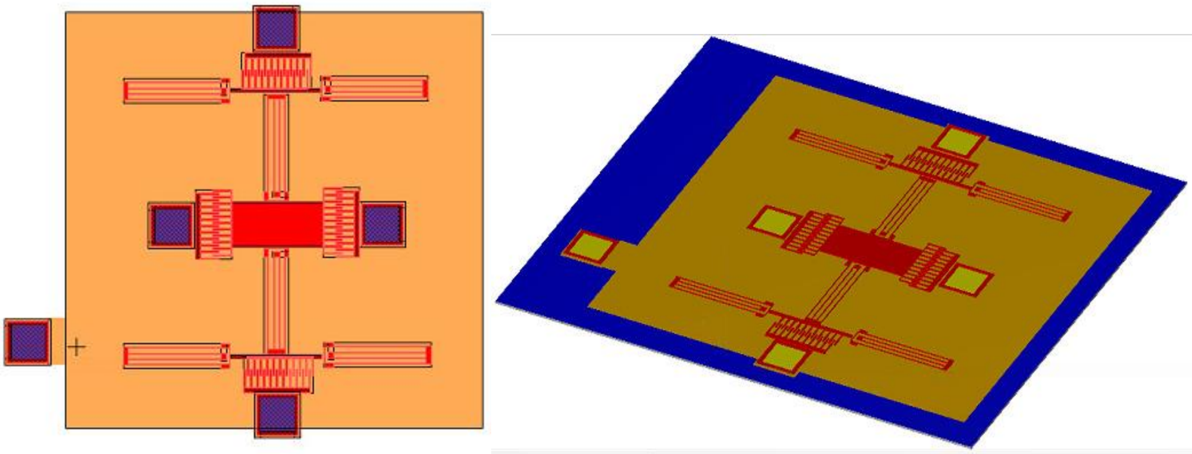


Fig 5.1: 3D Design using L-Edit

Steps of the fabrication process

1. The process begins with deposition of crystalline silicon of thickness 600 microns which is used as the substrate.
2. A layer of Silicon nitride is deposited on the substrate which acts as insulation between the substrate and the structure using LPCVD (low pressure chemical vapor deposition).
3. Next, a doped polycrystalline silicon layer (Poly0) is added to ground the stray charges.
4. Silicon dioxide layer is deposited next as an insulator, and it is the sacrificial layer with holes(anchors) to connect the upper polysilicon layer (Poly1) to the ground (Poly0). This is removed at the end of the process to free the first layer of polysilicon (Poly0).
5. Another layer of polycrystalline silicon (Poly1) is added, and this is used for all static and moving structures of the sensor. It is connected to the Poly0 layer both physically and electrically through the anchors.
6. A patterned photoresist layer is deposited on top of Poly1 layer where the Poly1 must be kept intact.

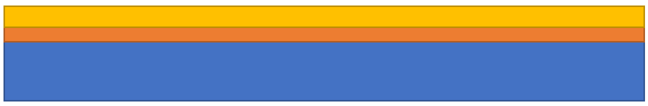
7. Poly1 layer is patterned by photolithography and etched out by using an etchant that dissolves the poly silicon but not the oxide layer.
8. Removal of the photoresist.
9. A PSG mask is deposited now on the Poly1 layer to dope it and to reduce the residual stress.
10. After the doping, the PSG mask is removed, and another patterned photoresist layer is added, and a metal layer is deposited on top of it.
11. Using the lift off process, the metal deposited on the patterned photoresist is removed and the rest of the metal is used as contacts.
12. The remaining oxide layer is etched by using Hydrofluoric acid and the process is complete.

Cross sectional view of the fabrication process

1)

2)

3)



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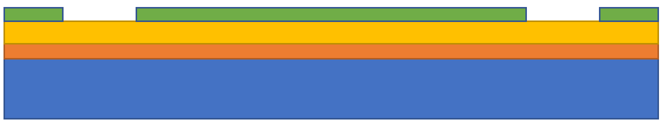

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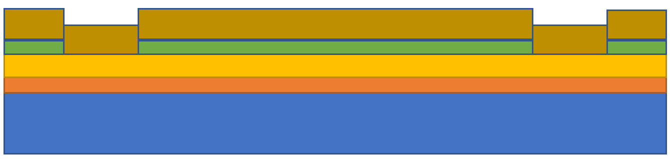

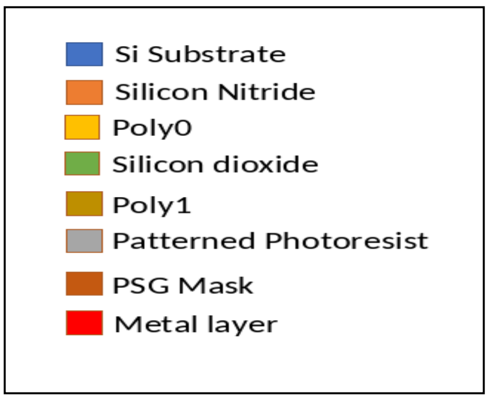

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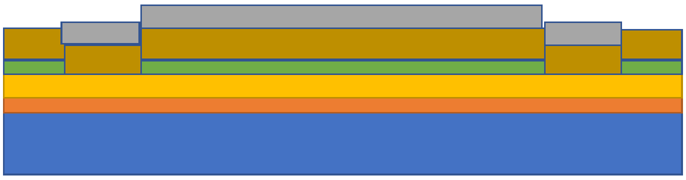

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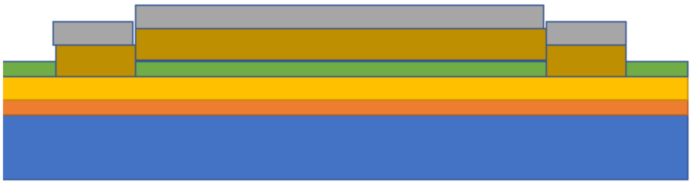

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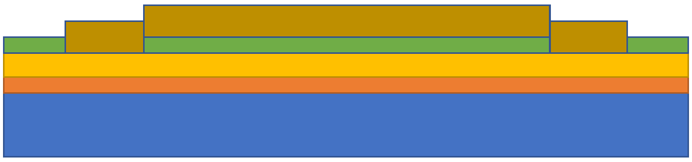
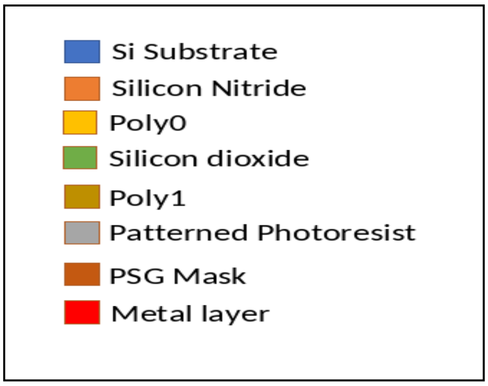
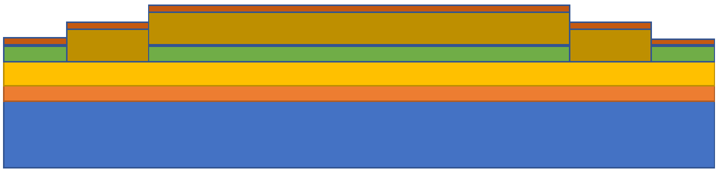



Si Substrate
Silicon Nitride
Poly0
Silicon dioxide
Poly1
Patterned Photoresist
PSG Mask
Metal layer

9)



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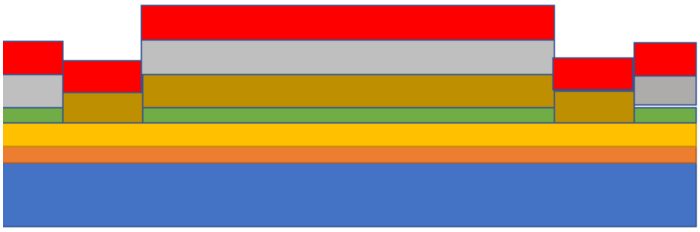

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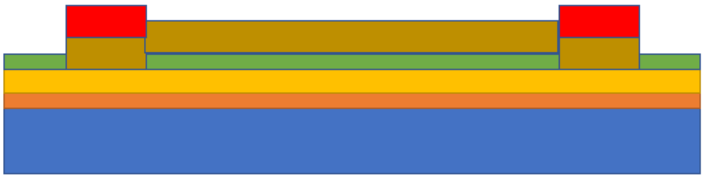

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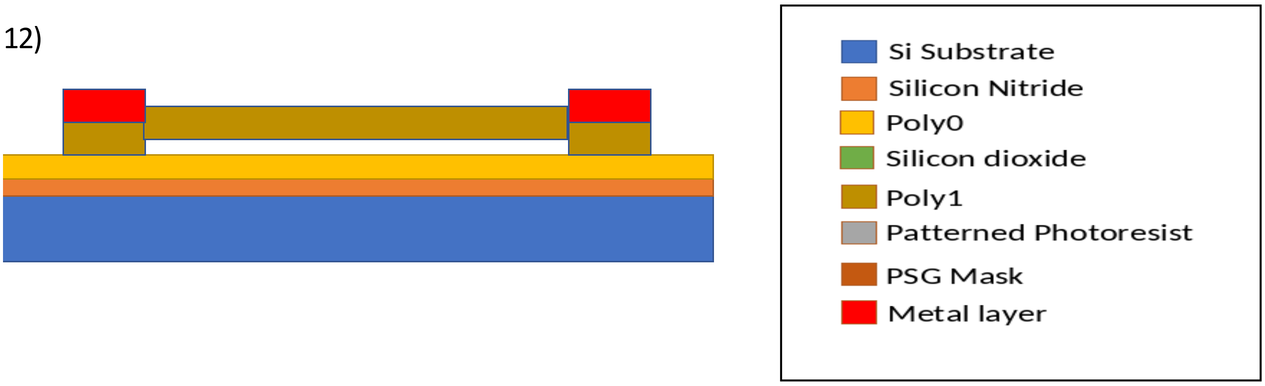
Si Substrate
Silicon Nitride
Poly0
Silicon dioxide
Poly1
Patterned Photoresist
PSG Mask
Metal layer

6 Dimensions & Calculations

Several calculations were necessary to theoretically plan the design concept in such a way as to achieve all requirements given at the beginning of the project. By taking the requirements and working backwards, it was possible to find the appropriate dimensions needed to fulfil those requirements. Trial and Error was a vital part of the project to get the best results possible.

Originally, the calculations were done using pen and paper to find formulas and define the sequence in which these formulas are used. This was then followed up using the numeric computing environment MATLAB. By entering the Formulas into MATLAB, it was possible to quickly change any dimensions/ numbers, which allowed the team to optimize the design.

Main Dimension of the angular rate sensor are shown in figure 6.1 below.

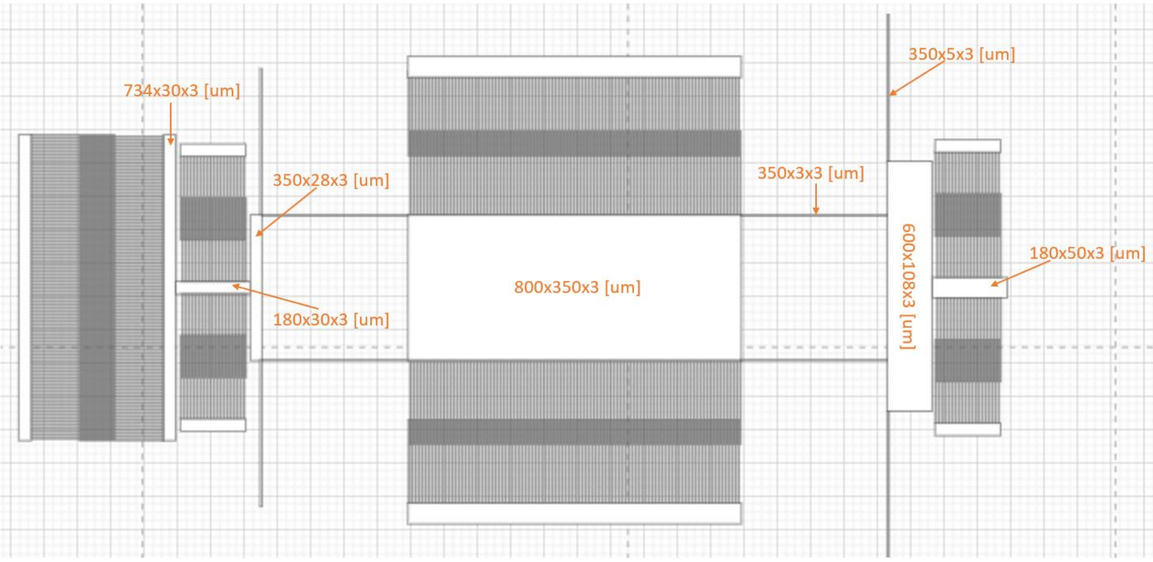

Fig 6.1

Further dimensions of the Sensor are:

- For the Sense Capacitors:
  - No. of Fingers N_s = 40
  - Length l_{sc} = 200 µm
  - Gap G_s = 2 µm
  - Height h_{sc} = 3 µm

- For the Comb Drive Actuator:
  - No. of Fingers N_d = 200
  - Length l_{cd} = 200 µm
  - Gap G_d = 2 µm
  - Height h_{cd} = 3 µm

Electrical Values of the Sensor:

- DC Voltage $V_{DC} = 15V$
- AC Voltage $V_{AC} = 1.5V$

Constants needed for the Calculations:

The quality factor was taken from the results of an experiment undertaken by students of the Department of Systems Engineering at the University of Waterloo in Waterloo, Canada. The experiment looked at measuring the quality factor of 3 different beams in MEMS Devices. [1.1]

- $\rho = 2300\ kg/m^3$
- $\varepsilon_0 = 8.854 \times 10^{-12}\ C/Vm$
- Youngs Modulus E = 160GPa
- $Q_d = 300$ [6.1]
- $Q_s = 300$ [6.1]

Main Calculations

Mass of the Drive Mass m_d:

$$m_d = 1.9322 \times 10^{-9}\ kg$$

Mass of the Sense Mass m_s:

Since the drive mass is also deflected when an angular rate acts upon the sensor, this mass must be added to the overall sense mass. Both Sense masses and all attached capacitive fingers are also included.

$$m_s = 2.6364 \times 10^{-9}\ kg$$

Moment of Inertia M:

$$M = w^3 \cdot \mathrm{h}$$

$M_d = 8.1 \times 10^{-23}\ kgm^2$ $M_s = 3.75 \times 10^{-22}\ kgm^2$

Spring Constant k:

$$k = \frac{3 \cdot M \cdot E}{l^3}$$

$k_d = 0.9068\ N/m$ $k_s = 4.1983\ N/m$

Resonance Frequency f:

$$f = \frac{1}{2} \cdot \pi \cdot \sqrt{\frac{k}{m}}$$

$f_d = 3.4 \times 10^4\ Hz$ $f_s = 6.27 \times 10^4\ Hz$

Angular Frequency ω:

$$\omega = 2 \cdot \pi \cdot f$$

$\omega_d = 2.14 \times 10^5$ rad/s $\omega_s = 3.94 \times 10^5$ rad/s

Resolution of acceleration for 1mg: $a = 1\times10^{-3} \cdot 9.81\ m/s^2$

Resolution of angular rate for 0.1°/s in radians:

$$\Omega_{rad} = \frac{\Omega \cdot 2\pi}{360}$$

$\Omega_{rad} = 0.0017$ rad/s

Velocity v:

$$v = \frac{a}{2 \cdot \Omega} \qquad [6.2]$$

$v = 2.8104$ m/s

Force for 2 Comb Drives F_d:

$$F_d = \frac{2 \cdot \mathrm{N} \cdot \varepsilon_0 \cdot \mathrm{h} \cdot V_{DC} \cdot V_{AC}}{G} \qquad [6.3]$$

$F_d = 1.2 \times 10^{-7}$ N

Drive mode Amplitude at Resonance Freq. x_d:

$$x_d = \frac{Q_d \cdot F_d}{w_d^2 \cdot m_d} \qquad [6.4]$$

$x_d = 4.06 \times 10^{-7}$ m

Sense mode Amplitude x_s:

$$x_s = \frac{2 \cdot \mathrm{i} \cdot \Omega \cdot x_d}{(w_s - w_d)(w_s + w_d)\frac{1}{w_d} + \frac{w_s}{Q_s} i} \qquad [6.5]$$

$x_s = -(7.11 \times 10^{-18}) - (2.77 \times 10^{-15})i$

Thus $x_s = 2.77 \times 10^{-15}$m

Phase angle φ:

$$\varphi = \tan^{-1}\frac{Im(x_s)}{Re(x_s)}$$

$\varphi_{rad} = 1.568$ rad

$$\varphi_{deg} = 89.85°$$

Operating Point x_0:

$$x_0 = \frac{\varepsilon_0 \cdot l_s \cdot h_s}{2 \cdot \mathrm{G} \cdot k_s} \cdot V_{DC}^2 \qquad [6.6]$$

$x_0 = 7.12 \times 10^{-14}$ m

First harmonic of the Force Amplitude in the operating point $F_{s,AC}$:

$$F_{s,AC} = \frac{N_s \cdot \varepsilon_0 \cdot l_s \cdot h_s}{2 \cdot G^2} \cdot V_{AC} \cdot V_{DC} \qquad [6.7]$$

$F_{s,AC} = 5.98 \times 10^{-7}$ N

Current Amplitude i_s:

$$i_s = V_{DC} \cdot \mathrm{Re}(x_s) \cdot w_d \cdot N_s \cdot \varepsilon_0 \cdot \frac{w_s \cdot h_s}{G_s^2} \qquad [6.8]$$

$i_s = 4.72 \times 10^{-16}$ A

Calculations for the Self-test part of the sensor

First the Coriolis force F_c at 100°/s was calculated:

$$F_c = 2 \cdot \mathrm{m} \cdot (\mathrm{v} \cdot \mathrm{w})$$

$F_c = 2.436 \times 10^{-8}$

Force of a comb drive actuator:

Next, it was possible to figure out how much voltage and how many Comb Drive fingers that the actuator needed to create the same force as the force that an angular rate of 100°/s would create.

$$N \cdot V^2 = \frac{F_c \cdot 2 \cdot \mathrm{d}}{\varepsilon_0 \cdot \omega}$$

N = 92 V = 8V

Calculations Conclusion

Using the above formulas and results, it was possible to find out how the angular rate sensor reacts for example: knowing the displacement of the 3 different masses, the force that are created and the current that the sensor outputs.
It is important to note that there are two ‘accelerometers. Therefore, the overall size and mass of the sensor is twice that of which is used in the calculations above. The reason for the 2 accelerometers is to be able to distinguish between a change in angular rate and acceleration.

7 Difficulties/Limitations

Only theoretical values:

All the above calculations are only theoretical and have not been tested in a real environment, therefore, one cannot be certain that the sensor will react exactly as calculated.

No actual testing. Simulation attempts failed:

As mentioned before all simulation attempts failed. This caused the design and its requirements to completely rely on the calculations. A simulation of the design concept would be able to either confirm the mathematics or correct any overseen issues.

Shortcomings on calculations:

Theoretically finding the measuring range of the angular rate sensor was known, however, calculating this value proved difficult.

Overall Size of the Sensor:
The overall size of the angular rate sensor is about 1mm, which isn't much of a problem for roll over applications in a vehicle since a car is comparatively large to the sensor. However, given a little bit more time with the project, the numbers could be adjusted as to decrease the overall size of the sensor. By weakening the springs, the mass can be reduced which means decreasing the overall size.

8 Conclusion

During the elaboration, an introduction to the topic of angular rate sensors was given. Different functional principles were highlighted and an overview of the state of the art was given. In addition, an exciting field of research was briefly explained, which attempts to solve current problems in sensor design.

Subsequently, the developed design was presented, which has the potential to meet the requirements of the task. This is a spring-mass system that includes differential sensing and is thus better protected against external interference. In addition, a DC voltage was fed in, which causes the system to oscillate by means of an additional AC signal. This offers the advantage that the characteristics of the sensor can be specifically adapted to the requirements.

After the design concept was developed, the necessary calculations for dimensioning were created using a MATLAB script. Following the dimensioning, the simulation and the validation of the selected parameters were to be carried out. Unfortunately, the system could not be tested in the simulation software S-Edit. Thus, only the developed MATLAB script was used as a control. The planned development steps marked in red could therefore not be executed.

- Advantages/Disadvantages Functional Principles
- Concept Design
- Calculation Parameters
- Structure of the design in S-Edit
- Adaptation of parameters
- Generation Manufacturing process

As a final assessment of this scientific elaboration, it can be stated that the selected design offers the potential to meet the requirements of the task. Regardless of the lack of validation of the parameters, a manufacturing process could be developed.

9 References

[1.0] Geen, John: New iMEMS Anuglar-Rate-Sensing Gyroscpe, Internet, 2021-02-15 (https://www.analog.com/en/analog-dialogue/articles/imems-angular-rate-sensing-gyroscope.html)

[1.1] Kraft, Michael: Micromachined Intertial Sensors: The State-of-the-Art and a Look into the Future, Internet, 2022-02-15. (https://www.researchgate.net/publication/270607756_Micromachined_Inertial_Sensors_The_State-of-the-Art_and_a_Look_into_the_Future)

[4.1] Kämper, K.(2020) " Lecture Notes- Sensors and Actuators". Pg.147 Fig.5.11

[5.1] Allen Cowen, Busbee Hardy, Ramaswamy Mahadevan, and Steve Wilcenski MEMSCAP Inc.*'PolyMUMPs Design Handbook'.* http://www.memscap.com/__data/assets/pdf_file/0019/1729/PolyMUMPs-DR-13-0.pdf

[6.1] Stefano Mariani (2015) '*Measuring the Quality Factor in MEMS Devices*', Department of Systems Design Engineering, University of Waterloo, Waterloo, Canada, pp. 1944

[6.2] Kämper, K. (2021) '*Problem 9: Angular Rate Sensor*'. 81632: Sensors and Actuators, Pg. 1 Formula: (5) Available at: https://www.ili.fh-aachen.de/ilias.php?ref_id=849649&cmdClass=ilrepositorygui&cmdNode=xt&baseClass=ilRepositoryGUI (accessed: January 2022).

[6.3] Kämper, K. (2021) '*Problem 10: Surface micromachined angular rate sensor*'. 81632: Sensors and Actuators, Pg. 3 Formula: (16) Available at: https://www.ili.fh-aachen.de/ilias.php?ref_id=849649&cmdClass=ilrepositorygui&cmdNode=xt&baseClass=ilRepositoryGUI (accessed: January 2022).

[6.4] Kämper, K. (2021) '*Problem 10: Surface micromachined angular rate sensor*'. 81632: Sensors and Actuators, Pg. 4 Formula: (20) Available at: https://www.ili.fh-aachen.de/ilias.php?ref_id=849649&cmdClass=ilrepositorygui&cmdNode=xt&baseClass=ilRepositoryGUI (accessed: January 2022).

[6.5] Kämper, K. (2021) '*Problem 10: Surface micromachined angular rate sensor*'. 81632: Sensors and Actuators, Pg. 4 Formula: (22) Available at: https://www.ili.fh-aachen.de/ilias.php?ref_id=849649&cmdClass=ilrepositorygui&cmdNode=xt&baseClass=ilRepositoryGUI (accessed: January 2022).

[6.6] Kämper, K. (2021) '*Problem 10: Surface micromachined angular rate sensor*'. 81632: Sensors and Actuators, Pg. 6 Formula: (30) Available at: https://www.ili.fh-aachen.de/ilias.php?ref_id=849649&cmdClass=ilrepositorygui&cmdNode=xt&baseClass=ilRepositoryGUI (accessed: January 2022).

[6.7] Kämper, K. (2021) '*Problem 10: Surface micromachined angular rate sensor*'. 81632: Sensors and Actuators, Pg. 6 Formula: (32) Available at: https://www.ili.fh-aachen.de/ilias.php?ref_id=849649&cmdClass=ilrepositorygui&cmdNode=xt&baseClass=ilRepositoryGUI (accessed: January 2022).

[6.8] Kämper, K. (2021) '*Problem 10: Surface micromachined angular rate sensor*'. 81632: Sensors and Actuators, Pg. 7 Formula: (41) Available at: https://www.ili.fh-aachen.de/ilias.php?ref_id=849649&cmdClass=ilrepositorygui&cmdNode=xt&baseClass=ilRepositoryGUI (accessed: January 2022).