MEMS Tuning-Fork Gyroscope

Cody Myers, Brent Sabo, Timothy Vella, Jeffrey Yeung

Abstract—In this report, we describe the preliminary design, fabrication, and layout of a MEMS tuning-fork gyroscope (overall area 1.5mm x 1.5mm) using comb drive actuation of a 585 µm x 605 µm proof mass. ED-NMOS circuitry is used to deliver DC and AC voltage to drive proof mass into resonant oscillations in one axis. The resultant coriolis force from an external torque crossed with the oscillations is sensed in the other axis by parallel plate capacitors adjacent to the proof mass, which is amplified through a read-out circuit to determine the external torque on the system. This design incorporates 29 comb fingers with a gap size of 5 µm. The entire structure is mirrored to provide a balancing effect to stabilize it during oscillations. Our calculated capacitance change under a 100 Hz angular rotation is 15.7fF, with an output voltage of 380mV resulting in a sensitivity of 0.011mV/º/s. Testing revealed that, while our device was overall correct, there were difficulties in achieving the desired drive oscillation amplitude and frequency. Though the device did not work as desired, this was an overall good learning experience. An important tip for future projects is to ensure that methods to test the device are incorporated into the design phase of various components.

Index Terms—gyroscope, inertial system, MEMS sensor, tuning-fork,

I. INTRODUCTION (YEUNG)

GYROSCOPES are extremely useful sensors for measuring the angle or rate of rotation, which in turn can determine acceleration and heading-direction. Traditionally, gyroscopes have found traditional use for inertial navigation (i.e., navigation systems) for military uses, by combining with measurements from an accelerometer, as well as platform stabilization (i.e., maintaining balance), by measuring rotations and applying torques with motors to cancel out this external force to maintain overall balance of the system.

However, within the last decade or so, gyroscopes have seen a widespread popularity in the form of micromachined silicon gyroscopes, incorporated into a vast range of mobile electronic devices today from smartphones to GPS units to gaming controllers. Added to many electronic devices, they are used as a sensor for rotation and orientation or as an input device, allowing the user to torque the device to generate an action. They are often used in conjunction with 3-axis accelerometers to provide a more reliable measurement of the position of the device as well [1].

In general, macro-scale gyroscopes measure angular momentum, typically with some form of spinning wheel or disk that is free to assume any orientation. External torques that alter the spinning element's position can be sensed and thus measured. Gyroscopes based on other operating principles exist, including optical and quantum gyroscopes. MEMS gyroscopes use similar physics but have a different type of moving element.

Due to their design with low part counts and highly scalable fabrication processes, MEMS gyroscopes are relatively cheap compared to macro-scale gyroscopes. This enables them to become economically widespread, which partially explains their prevalence in consumer electronic devices. Additionally, they can be fabricated onto existing pcb and be used in conjunction with all the sensors already on these devices, for example on smartphones.

There are a few major types of MEMS gyroscopes, categorized by their varying designs and principles of operation. Some of these utilize tuning forks (described in this paper), vibrating wheels, or resonant solids. Vibrating wheel gyroscopes utilize a spinning wheel that rotates with external stimulus. Resonant solids gyroscopes measure the resonant vibrations of a connected mass due to the external torques. There are also optical devices utilizes lasers, but these are less used [2].

In this report, we will focus on the tuning-fork gyroscope as our type of choice. We chose to design a tuning-fork gyroscope due to its technical challenge as well as its broad application. In particular, besides being one of the most prevalent gyroscope designs, the tuning-fork gyroscope is used in the iPhone 4 and other smartphones [3]. Thus, it seems to be a particularly ubiquitous sensor in our day-to-day lives. We wanted to better understand it and attempt to create our own.

We will first review the specific applications and operating principles of the tuning-fork gyroscope. Then we will discuss the proposed design and calculations, simulations, and fabrication layout for our MEMS tuning-fork gyroscope.

II. TUNING-FORK GYROSCOPES (YEUNG)

A. Mechanical Structure

The tuning-fork gyroscope is composed of several components, depicted in Figure 1. A proof mass is connected to a spring composed of a series of thin beams designed to allow compression in both planar axes (x and y). There are two such sets of springs to allow for balance of the proof mass such that while in motion it will not flip. Sense electrodes are used to detect the motion. On the other axis, adjacent to the proof mass, are the comb fingers, one set connected to the proof mass and the other to the drive electrode. This composes a set of inter-digitated varying-overlap capacitors, which facilitates
the transfer of the electric potential applied to the drive electrode to a capacitive force on the proof mass. This force drives the proof mass to move. Due to the nature of the drive force and the connection to the springs, the proof mass oscillates back and forth.

$$\ddot{a}_{\text{coriolis}} = 2\Omega \times \dot{v}$$  \hspace{1cm} (2)

$\Omega$ is the external angular velocity, and $v$ is the object's velocity.

In order to achieve a high performance gyroscope, the two axes must be mode-matched. This means that their respective resonance frequencies must near each other as possible, causing them to oscillate in-phase and thus allow maximum transfer of force from one axis to the other. In order to have the same resonance frequency, spring constants for each of the oscillations must be the same, as these are related by the following equation:

$$\omega = \sqrt{\frac{k}{m}}$$  \hspace{1cm} (1)

$\omega$ is the resonance frequency, $k$ is the spring constant and $m$ is the mass of the moving object [1]

B. Coriolis Effect and Overview

Tuning fork gyroscopes are a subset of the category of coriolis vibratory gyroscopes, which function based on the Coriolis Effect. The Coriolis Effect is the acceleration experienced by a moving object in a rotating reference frame (illustrated in Figure 2), such as by the rotation of the Earth or by any particular torque applied to a small device. In the case of an actual tuning-fork, the arms can be struck to cause them to oscillate in one axis while the tuning-fork is itself rotated about its main axis, which causes oscillations in the axis perpendicular to the arm oscillation axis. This acceleration can be equated as:

$$\ddot{a}_{\text{coriolis}} = 2\Omega \times \dot{v}$$  \hspace{1cm} (2)

In our case, the angular velocity of the reference frame is given by the external stimulus. The velocity of the particle is caused by our drive force, which we will explain later. This acceleration is what causes the coupling between our drive-axis and our sense-axis. The proof mass is driven to resonance in the drive-axis, causing the mass to experience the Coriolis force in the sense-axis. This causes oscillations in the sense axis, which can be detected through the parallel plate capacitors to determine the aforementioned external angular acceleration.

C. Drive Mode

The drive mode is used to keep the proof mass in constant motion, ready to sense external torques. It is controlled by the drive electrode, which applies an electric potential to the comb fingers to actuate the proof mass and cause it to oscillate at the resonant frequency of the springs. The force on the proof masses from the drive electrodes is a function of the applied voltage, as well as the design parameters of the comb structure.

$$F \approx V^2 n e_0 \frac{h}{g}$$  \hspace{1cm} (3)

$n$ is the number of comb fingers, $h$ is the finger height, and $g$ is the gap between the moving and fixed fingers [6]

The motion in the drive-axis can be modeled as a dampened simple harmonic spring oscillation with an applied force $F$.

$$m \frac{d^2x}{dt^2} + D \frac{dx}{dt} + kx = F$$  \hspace{1cm} (4)

$m$ is the mass of the proof mass, $D$ is the dampening coefficient, $k$ is the spring constant [6]
The dampening coefficient is governed by the quality factor, \( Q \), of the system, which is assumed to be about 10000, taken from literature values as used to simulate commercial and research gyroscopes. This relation is equal to [6]:

\[
D = \frac{\sqrt{km}}{Q}
\]  
(5)

Solving this differential equation yields a time-dependent oscillation solution with maximum amplitude and frequency governed by the drive force and drive frequency. In this case, since the drive frequency is also the resonant frequency of the spring, the oscillation frequency is the resonant frequency. The equations can be solved to give the maximum drive amplitude:

\[
x_0 = \frac{2ne_0h}{gk}V^2Q
\]  
(6)

The velocity of the mass is maximized at zero acceleration. This maximum velocity is derived to be

\[
v_0 = \frac{2ne_0h}{g\sqrt{km}}V^2Q
\]  
(7)

### D. Sense Mode

The sense mode is a result of the oscillations in the drive mode, causing the proof mass to move in the direction of the sense electrodes from the Coriolis force. This movement is detected by parallel plate capacitance changes due to the movement. The change in gap distance can thus be sensed. This is computed as follows:

\[
C = \frac{\varepsilon_0 A}{d}
\]  
(8)

\( A \) is the area of the sense electrode, \( d \) is the gap distance to the proof mass [6]

The displacement in this direction is solved as follows:

\[
y_0 = \frac{2v_0\Omega}{\omega\sqrt{km}}Q
\]  
(9)

This gives a final capacitance of

\[
C_1 = \frac{\varepsilon_0 A}{d-y_0}
\]  
(10)

which is what is measured through the output circuitry.

### E. Final Calculations

A calculation of \( \Omega \) can be derived based on the value of the maximum oscillation velocity \( v_0 \), sense electrode capacitance \( C_1 \), and sense-axis amplitude \( y_0 \) by calculating through equations (8), (9) and (10).

### III. MEMS Design (SABO)

We now shift to discussing our proposed design, first with the MEMS then the ED-NMOS.

#### A. Overview

To create a gyroscope based on the tuning fork principle, two identical, coupled proof masses are driven to the structural resonant frequency. The maximum sensitivity is achieved by operating both the drive and sense modes at an equivalent resonance [1]. Additionally, the proof masses are driven asymmetrically to promote balanced operation under high-frequency vibration. Without this, the gyro may experience torsional force out of plane. Meandered beam structures are attached at the top and bottom of each proof mass to allow vibration in both the drive and sense directions. The block diagram in Figure 3 shows the operation of the MEMS structure. A summary of the final design parameters for the MEMS structure is shown in Table 1.

---

**Proof Mass**

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>585 µm x 605 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>94.8 ng</td>
</tr>
</tbody>
</table>

**Comb Drive**

<table>
<thead>
<tr>
<th>Number of Fingers</th>
<th>29 fingers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>25 µm</td>
</tr>
<tr>
<td>Width</td>
<td>5 µm</td>
</tr>
<tr>
<td>Gap</td>
<td>5 µm</td>
</tr>
<tr>
<td>Initial overlap</td>
<td>10 µm</td>
</tr>
</tbody>
</table>

**Sense Electrodes**

<table>
<thead>
<tr>
<th>Length</th>
<th>280 + 285 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>50 µm</td>
</tr>
<tr>
<td>Gap</td>
<td>5 µm</td>
</tr>
<tr>
<td>Spring Constants</td>
<td>34.2 N/m</td>
</tr>
</tbody>
</table>

Table 1. Summary of MEMS design parameters per side of system

---

Fig. 3. Block diagram of a MEMS tuning fork gyroscope. The orange block represents the sensing parameter (rotation). Details of the supporting drive and sense circuitry are omitted.
B. Drive Electrodes

Each proof mass is pulled outward simultaneously by two fixed drive electrodes. The drive electrodes are separated mechanically, but connected electrically to achieve balanced operation for resonant coupling. Inter-digitated comb fingers create a linear actuation force between the proof masses and drive electrodes, as shown in Figure 4. The proof masses are grounded, whereas the drive electrodes receive a DC-biased AC voltage from 0 to full amplitude to create the periodic pulling force required for oscillation.

![Figure 4. A comb-drive linear actuator is designed with equivalent spacing on either side of the center comb finger to offset the attractive forces. A potential difference between the fingers creates a force into the fixed comb from the center finger’s fringe capacitance [6]](image)

The height of the comb fingers is predetermined at 100 µm based on the silicon wafer thickness. The gap was designed at 5 µm, to obtain a maximum attractive force. There are a total of 29 fingers on each proof mass based on the previous parameters and proof mass size. Ideally a larger force would be generated with more fingers and a smaller gap size to increase sensitivity of the gyro, but fabrication limitations dictate this design. Because the attractive force increases with displacement, consideration must be taken to avoid exceeding the spring force, known as *pull-in*, where the fingers snap together [6]. As a rule of thumb, pull-in occurs when displacement exceeds one third of the original gap. Calculations and simulations yielded linear displacement at no more than 3 µm, so the tips of the fingers were designed 10 µm from the base of the opposing fingers.

C. Sense Electrodes

External in-plane rotations will create oscillations orthogonal to the drive mode, based on the Coriolis force. In order to sense the reactive oscillations, fixed electrodes are positioned along the proof masses to create varying gap capacitors. The electrodes only span one side of each proof mass, noting that electrodes on both sides would null one another (one gap would increase the same amount the opposing gap decreased). Additionally, the electrodes are on opposite sides of each proof mass since the drive oscillations are symmetric (creating sense-mode oscillations that are simultaneously opposite one another).

By spanning one entire side to maximize sensing signal (apart from the spring connection) of each proof mass, the total capacitive length is 565µm. Space was allocated to accommodate oscillations in the drive mode that may bend the spring connection without contacting the sense electrodes. Based on the 100-micrometer wafer thickness, the rest sense capacitance is 104.4 fF. The sides opposite the sense electrodes also contain standoff portions of the substrate that extend 1 µm closer to the proof mass than the electrodes. Therefore, the proof mass will crash into the standoffs before the electrodes in the event of a rotation rate exceeding the gyroscopes sense range.

D. Balance Electrodes

Along the bottom (outermost) leg of each spring structure, additional electrodes are included for testing purposes. During actual operation, the electrodes could be applied to balance the sense resonance mode with that of the drive [7]. For our purposes, we could create a sense-direction displacement through an applied voltage during the testing process.

E. Spring Structures

Each proof mass is supported on the two sides about the drive electrode with a meandered spring structure. The original design contained a single 8-µm-wide spring connecting each side to the anchor. To avoid any torsional instabilities related to fabrication imperfections, the design was improved to utilize a double spring structure with each spring 5 µm wide, spaced 10 µm apart, with a fixed anchor in the middle. The structure was required to have an equivalent spring constant in both the drive and sense directions to enable equivalent resonant frequencies. Preliminary calculations treated the legs along the spring direction as fixed points connecting the perpendicular legs, which were all treated as guided beams in series. This first iteration included two spring structures on either side of each of the two proof masses. However, these springs were physically disconnected from one another.

A final iteration of the model was made to connect the spring structures adjacent to one another to couple the two systems together. The spring constant was also doubled to account for the symmetrical structure in parallel connecting to the opposing side of the proof mass. An initial design was created in COMSOL using the calculated spring dimensions. Adjustments were made to the dimensions until the drive and sense directions were of the same spring constant.

IV. ED-NMOS DESIGN

A. Drive Circuit (MYERS)

*Drive Circuit Overview*

In order for our MEMS Tuning Fork Gyroscope to work it must be driven at a resonance frequency. The drive circuit
consists of an oscillator, a DC Bias and a summing configuration to get an AC + DC signal. This signal will then act as input to the drive electrodes of the gyroscope. Figure 5 shows the topology used for designing the drive circuit.

This a common circuit for level shifting which is what we wish to do to avoid negative forces from the negative part of the sine wave. This circuit will produce a sine wave that is purely positive with a voltage offset that we choose. The resistor values were kept the same across this topology to keep gain ratios 1:1.

Fig. 5. Schematic of Drive Circuit

**Ring Oscillator**

The drive circuit requires an oscillatory signal as input into the operational amplifier. The oscillation must be at resonance frequency which is 3005Hz. Ring oscillators are normally used for high frequencies, so in order to slow down the oscillation we added capacitive loads at each inverter output to mimic a sine wave at 3005Hz.

Fig. 6. Ring Oscillator (C = 2.45nF)

The inverters were sized 2:1 to give us symmetric skewing to mimic the sine wave. The capacitors are considerably large so they will be off-chip. The capacitors slow the oscillation to look like a sine wave rather than the normal square wave you see with ring oscillators.

**The Operational Amplifier**

In order to form this function of adding the DC bias to the AC signal we needed an operational amplifier. We chose to go with the design in Figure 7 because the original specifications indicate high slew rate, bandwidth, and a reasonable gain [11].

![Operational Amplifier Schematic](image)

The first half of the schematic shows the input stage, differential stage, and level shifter. The right half shows the output stage. When designing the operational amplifier we kept the elements relatively the same except for the sizing since for our process the parameters are different which lead to different voltage thresholds to keep the transistors in saturation mode.

In designing the operational amplifier we first started with the input stage and differential stage shown in Figure 8.

![Differential Stage](image)

We designed the three depletion loads to be large and equal to give a high output resistance for the biasing transistor M5. M2A and M2B are half the size of M1A and M1B. M1A, M1B, M2A, and M2B are designed this way to get a total of 3 times the current coming from a single depletion load.

The level shifter stage was designed by input of initial sizing for the design and then adjusting these sizes to make sure all the transistors were in saturation mode. The capacitors were not determined in this stage until after the operational amplifier was complete. To determine the capacitor values we used multiple simulations to see what capacitors would give maximum bandwidth. The capacitor values for the capacitors were as follows, CC = 2.3pF and CB was 0.5pF.
The output stage was originally designed with M33 being an enhancement device as shown in Figure 9. We changed this design to M33 being a depletion device to allow for more voltage swing at the output. M35 and M36 were kept very large to drive large capacitive and resistive loads.

B. Readout Circuit (VELLA)

Overview

In order to read the output signal of our MEMS Tuning Fork Gyroscope we designed a multi-stage circuit that acts as both an amplifier and a band-pass filter. The amplification stages are needed to increase the magnitude of the initial output current because it is in the range of 10-20 fA. This output current is created due to the Coriolis induced y-axis displacement of the proof mass, which changes the rest capacitance of the sense electrodes and generates a motional current \( i_{\text{motional}} \) [9]. This current is determined by a number of factors such as: the fixed DC potential \( V_{\text{DC}} \), the effective mechanical quality factor \( Q_{\text{eff}} \), the initial resting sense capacitance \( C_{\text{so}} \), the magnitude of x-axis displacement \( d_{\text{x}} \), the initial sense gap \( d_{\text{so}} \), and the input rotation \( \Omega_{z} \).

\[
\frac{2\pi V_{\text{DC}} Q_{\text{eff}} C_{\text{so}} g_{\text{drive}} \Omega_{z}}{d_{\text{so}}}
\]

Using the previous simulation results we are able to estimate the value of this output current as \( i_{\text{IN}} = 12.97 \sin(3.05 \text{ kHz}) \) fA. This estimate was calculated considering maximum displacement of the proof mass in both the x-axis and y-axis, which therefore makes \( i_{\text{IN}} \) the approximate maximum output current that we will use to design the output circuitry.

In the first stage of the readout circuit we need to convert this output current into a voltage signal. We accomplished this by using a transimpedance amplifier, which is an inverting amplifier with zero source impedance. After the transimpedance stage the voltage signal is filtered using a band-pass filter known as a Deliyannis filter to eliminate any noise signals with frequencies greater than 3.5 kHz or less than 2.5 kHz [10].

Together these two stages are able to produce a noise free signal with amplitude that can be measured using the test equipment available in the lab. From this output signal we can deduce the amount of rotation that occurs in our MEMS device by analyzing the signals amplitude and change in frequency.

Transimpedance Amplifier Circuit

The first stage of our readout circuit is the transimpedance amplifier. In this stage we convert the output motional current from our gyroscope into a voltage signal. The transimpedance amplifier acts as a current to voltage converter while also providing gain proportional to the feedback impedance. A layout of this stage can be seen below in Figure 10.

\[
V_{\text{out}} = -(i_{\text{IN}} * R)
\]

By choosing the feedback resistor we can amplify the input current to create an output voltage with amplitude in the micro-volt range. By choosing \( R = 750 \) MΩ we find that \( V_{\text{out}} = 9.73 \sin(3.05 \text{ kHz}) \) µV. The drawback to using such a large impedance in the feedback is that we must use an off chip resistor which will cause inherent parallel feedback capacitance. We have since learned that using an impedance resistor would be impossible because the op-amp would be unable to support it and thus cause virtual ground not to exist. After this stage we then send this output voltage through a Deliyannis filter to eliminate any noise signals from the mechanics our of MEMS device.
**Deliyannis Band-Pass Filter**

One type of band-pass filter which uses only one op amp is called a Deliyannis filter. This filter operates to pass a very narrow band of frequencies, which makes it ideal for eliminating noise outside of this range. In the design of this stage we needed five components in addition to the op amp (three resistors and two capacitors). To power this op amp we supplied a ±5 V as labeled by (+Supply and –Supply on the next figure). A layout of this filter can be seen below in Figure 11.

In the above figure, $V_{in}$ represents the output voltage from the transimpedance amplifier and $V_{out}$ represents our final output voltage. A Deliyannis filter operates on the following set of equations:

\[
\begin{align*}
    f &= \frac{1}{2\pi R_1 C} \\
    R_2 &= \frac{R_1}{19} \\
    R_3 &= 20 \times R_1
\end{align*}
\]

From our previous measurements we know that the frequency of our output signal will be approximately 3.05 kHz. Using (13), where $C = C_1 = C_2 = 50 \text{ pf}$, we calculated a resistor value for $R_1 = 1.044 \text{ k}\Omega$, which in turn results in $R_2 = 55 \text{ k}\Omega$ and $R_3 = 20.873 \text{ k}\Omega$, from (14) and (15) respectively.

**V. MEMS SIMULATIONS (YEUNG)**

MEMS simulations were done in COMSOL Multiphysics 4.3. The 3D model including both sides of the mirrored structure is shown below in Fig 12.

In Figure 13, we have the simulation of the drive displacement on the proof mass in the first model iteration, resulting in about $8.43 \mu\text{m}$ at an applied force of 44.3 nN. A similar simulation was run for the sense-axis displacement.

However, we realized that this model does not couple the two systems together. This would prevent the balancing effect originally desired, so the spring structure was modified to connect together on either side of the proof masses, as shown in Figure 14. A large anchor block on either side connects the springs together. In so doing, the two systems are connected. Additionally, emergency stopper blocks were added to the sense-axis to prevent the proof mass from oscillating enough to cause pull-in voltage and thus short out the sensor. All these changes may affect the performance and thus had to be re-simulated.
Using this model, we applied a force of 1µN in each of the x- and y-directions to the proof mass (separately) to test its spring constants in the stationary simulation, and thus compute the resonance frequencies to ensure that they were the same within tolerances. The larger blocks connected to the springs were held as anchors. This is shown in Figure 15 for the drive-direction. Spring constants were equivalent to the calculated values of 34.2 N/m in both modes, giving the resonance frequency of 3.05 kHz.

Static capacitance values were determined by applying a 1V potential to the drive and sense electrodes and testing the device in air as shown in Figure 16, for one of the two proof mass’s comb fingers. For the drive mode, the rest capacitance is simulated as 31.4 fF. For the sense mode, the rest capacitance is simulated as 51 fF.

Displacement values were determined by applying an x- or y-direction force on the proof mass equal to the calculated force applied, either from the applied electric potential or the resultant Coriolis force generated. The model was then simulated in a time-dependent case with the input force as a sinusoid. The maximum displacement on the proof mass that resulted from this simulation was then to be recorded and used in calculations. However, we encountered errors in attempting to simulate this in the time-dependent case, which is necessary in order to achieve resonance. Unfortunately, COMSOL has difficulty with these types of studies and we encountered some errors in simulating the results. As such, the maximum oscillations are not explicitly certain, though expected to be similar to the previous simulations and calculated values. This makes it not possible to calculate the simulated capacitances under drive as the displacements are not simulated.

Finally, a table of the calculated parameters is shown in Table 2. Calculations were made assuming a 100Hz value for the external angular velocity, $\Omega$, a 5V DC and 1V AC input potential, and a conservative quality factor of 4000. This resulted in a calculated drive force of 13.3 µN and a coriolis force of 39.0 nN. This results in a sensitivity value of 0.011mV/º/s.

<table>
<thead>
<tr>
<th></th>
<th>Driving</th>
<th>Sensing</th>
<th>Anchors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Displacement</td>
<td>6.21 µm</td>
<td>4.57 µm</td>
<td>3.05 kHz</td>
</tr>
<tr>
<td>Rest capacitance</td>
<td>53.1 fF</td>
<td>104.4 fF</td>
<td>3.05 kHz</td>
</tr>
<tr>
<td>Capacitance under drive</td>
<td>20.1 fF</td>
<td>120.1 fF</td>
<td></td>
</tr>
<tr>
<td>Capacitance change</td>
<td>33.0 fF</td>
<td>15.7 fF</td>
<td></td>
</tr>
<tr>
<td>Resonance Freq</td>
<td>3.05 kHz</td>
<td>3.05 kHz</td>
<td></td>
</tr>
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</table>
VI. ED-NMOS SIMULATIONS

A. Drive Circuit Simulations (MYERS)

Figure 17 shows the simulation for the ring oscillator in the drive circuit with the three capacitive loads of 2.45nF. The ring oscillator gives us 3005Hz oscillation frequency which is the resonance frequency of the gyroscope. Note in this simulation, the lower voltage was ground so the offset was 2.5V. In our circuit we use 5V for Vdd and -5V for Vss so the offset will be 0 for the ring oscillator.

The simulations for the specifications well exceed our needs for the operational amplifier considering our signal is relatively slow. The slew rate and bandwidth satisfy our needs with the signal of the oscillator only being at 3005Hz, as shown in Table 3.

<table>
<thead>
<tr>
<th>Op Amp Spec by Simulation</th>
<th>Value</th>
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<tbody>
<tr>
<td>Slew Rate</td>
<td>4 V/µs</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>~ 1 MHz</td>
</tr>
<tr>
<td>Open-Loop Gain</td>
<td>~ 53 dB</td>
</tr>
<tr>
<td>Common Mode Range</td>
<td>-2.1 V - 2.3 V</td>
</tr>
</tbody>
</table>

Table 3. Operational Amplifier Specifications. Vss = -5V, Vdd = 5V.

In Figures 18 and 19, the simulation setup and results are shown. In this simulation our Op Amp that we designed above is used. The results are a completely positive sine wave at 1.9V DC.

B. Read-out Circuit Simulations (VELLA)

To minimize fabrication we used the same op amp model designed for our drive circuitry in all of our readout circuit simulations. Using this op amp model we were able to assemble the circuit diagram below, where stage 1 represents the transimpedance amplifier and stage 2 represents the Deliyannis band-pass filter.
In order to simulate the current from the gyroscope we used a sinusoidal voltage with amplitude 12.97 fA and a frequency of 3.05 kHz. After running an AC analysis on this system we were able to create the following graphs showing both the AC gain and phase of our entire readout circuit.

Figure 21 shows that our circuit is successful in creating a band pass filter centered around 3.05 kHz with cutoff frequencies at 2.8 kHz and 3.3 kHz. These cutoff points fall within our estimated values of 2.5 kHz and 3.5 kHz, which only improves the amount of noise that can be filter out of our signal.

Figure 22 shows that the phase of our entire readout circuit stays within approximately ±80°. Because this system does not exceed ±180° we can see that the readout circuit does not reach an unstable state.

In addition to these simulations another round of simulations were conducted with additional parallel capacitors added across any off chip components and found that the phase of our circuit dropped by approximately 90° for every frequency. Figure 23 below shows the actual phase of our readout circuit with these added capacitors.

Following the AC analysis on our readout circuit we then performed a transient analysis to find the magnitude of our final output voltage. As can be seen in Figure 24 below our maximum ac voltage magnitude is approximately 380 mV.

By designing the circuit to reach the millivolt range we both amplified the output signal above the micro-volt noise range amplitude as well as make it measurable using the test equipment available in the lab.

VII. MEMS FABRICATION (SABO)

The MEMS device is fabricated using Silicon-on-Glass (SOG) technology in a four-mask process. Starting with a 500 µm-thick Borosilicate (Pyrex) glass wafer, the first mask defines etch areas. The second mask patterns electrodes on the glass, after which a 100 µm-thick p-doped Silicon wafer is anodically bonded to the top of the glass. The third mask patterns electrodes on the Silicon wafer. Finally, the fourth mask defines the areas of a Deep Reactive Ion Etch (DRIE). The mask layouts are created in Cadence Virtuoso and later transferred to physical masks made of glass and Chromium. The final structure of the process is depicted in Figure 25.
A. Glass Etch

The glass etch is used to create 3 \( \mu m \)-deep wells for the purpose of releasing Silicon structures in the DRIE step. A thin film of Chromium is deposited on the glass wafer and then chemically etched as defined by a photoresist mask to reveal the areas of glass to be etched. Next, the glass is etched in HF acid, after which the photoresist and Chromium are stripped. Based on pressure differentials during the DRIE etch, all etch areas must be connected, and must all connected to an outer perimeter.

The proof masses and supporting spring structures will need to be released Silicon structures. The glass etch is defined to create a recess corresponding to the areas beneath the released structures. The glass etch layout is shown in Figure 26.

B. Glass Electrode

The glass electrode is used to create electrical connections as well as capacitive electrodes. Additionally, it can be applied in recessed areas below large Silicon structures to prevent undesired anodic bonding in those sections. The electrode is applied using a lift-off process. Photoresist defines areas not receiving the metal film. Next, Chromium is evaporated onto the wafer to promote adhesion, after which the main coating of Platinum is evaporated. Stripping the photoresist eliminates the metal from all areas except those which it defined.

The glass electrode electrically connects two of the sense electrodes based on discontinuity in the Silicon across the spring structure. Additionally, the recess below the proof masses receives a large electrode electrically connected to the Silicon bulk. This ensures the same electric potential for the recess and the proof masses during anodic bonding. The glass electrode layout is shown in Figure 27.

C. Anodic Bonding

After all preprocessing of the glass wafer is completed, the p-doped Silicon wafer is attached to the glass wafer using a high-voltage, high-temperature anodic bond. The pair is heated to 300°C and 1,000V is applied across the sandwich to create a very strong bond.

D. Silicon Contacts

A thin-film aluminum is applied to the Silicon wafer to create electrical contacts and other connections. Aluminum is first evaporated onto the wafer. Next, photoresist is defined to coat the desired contact areas. Finally, the aluminum is etched followed by a strip of the photoresist.

The aluminum defines 36 contacts on the wafer, with 9 on each edge. Additionally, small strips on the proof mass adjacent to strips on the bulk will aid in testing the drives
deflections under applied voltages. The aluminum electrode layout is shown in Figure 28.

![Fig. 28. The enclosed dotted areas correspond to the portion of the Silicon wafer that will be coated in a thin film of Aluminum](image)

**E. Deep Reactive Ion Etch (DRIE)**

The DRIE is used to etch completely through the Silicon for electrical isolation and structure release. Normal RIE is an isotropic process, but DRIE uses a special gas chemistry to create a polymer on the side walls as it etch proceeds. The mass transport time of the etching ions is dependent on the width of the etch, causing DRIE Lag (varying etch depths) [8]. Therefore, we must take special care to keep a consistent etch width, preferably the minimum allowable.

DRIE releases our Silicon proof mass and connecting spring structures. Also, it electrically isolates portions of the conductive Silicon to form connections to the multiple electrodes. The DRIE layout is shown in Figure 29.

![Fig. 29. The colored areas represent the portion of the Silicon wafer that will be consumed in the DRIE step](image)

**F. Final Fabrication**

The fabrication yielded multiple copies of the silicon-on-glass wafers. The times spent under DRIE etching varied for different wafers in an effort to produce copies having an ideal etch depth. This step was critical to our design because we needed complete release of the proof masses and their spring supports for a working sensor. The proof masses were fully released on the wafers that underwent a 40.5 minute DRIE. The final fabricated device is shown in Figure 30.

![Fig. 30. Microscope image of the final MEMS tuning fork gyroscope](image)
VIII. ED-NMOS FABRICATION

A. Drive Circuit Fabrication (MYERS)

The 2.45nF capacitors in the oscillator circuit are too large to be fabricated on chip so they will be connected externally. Figure 31 shows the fabrication layout of the ring oscillator.

B. Read-out Circuit Fabrication (VELLA)

The two stages in the next figure show the op amp we previously designed as well as new connections and a pair of on chip resistors. The size of this op amp allowed us to fit both stages of the readout circuit onto a single die with the addition of several off chip components. Figure 32 depicts our NMOS layout of our readout circuit, which outline where the transimpedance amplifier (stage 1) and the Deliyannis filter (stage 2) lie on the die.

To fabricate these resistors we used the known sheet resistance for polysilicon of \( 14.2 \, \frac{\text{ohm}}{\text{square}} \) with the following equations:

\[
R_1 = 14.2 \times \frac{L}{W} = 14.2 \times \frac{441.12}{6} = 1.04398 \, \text{k}\Omega
\]

\[
R_2 = 14.2 \times \frac{L}{W} = 14.2 \times \frac{23.24}{6} = 55.0013 \, \Omega
\]

Plugging these new values into the previous simulations did not significantly alter any of the results, which means we can proceed without having to re-evaluate any other components to account for these small differences. All of the other components needed for our readout circuit proved to be too large to manufacture within our design constraints and will have to be connected externally.

IX. TESTING

A. MEMS Testing

The realistic sensing conditions of the tuning fork gyroscope could not be tested in the lab with the available equipment. The device would require an input rotation while under vacuum and connected to the testing equipment. The testing instead focused on the more specific functions of the overall device operation.

The first test was the proof mass deflection under an applied drive electrode voltage. Powering each drive electrode with 30 VDC caused a 0.5 micrometer outward movement of each proof mass. Theoretical and simulated deflections were much greater, and at much lower voltages. The limited deflection likely results from the doubled spring support structure. The addition of a second spring to each side increased the stiffness, and therefore the repulsive force to the drive electrodes. Additionally, a larger electrostatic drive force could have been achieved by designing the comb finger gap at the minimum feature size of 3 micrometers rather than 5 micrometers. The deflections were expected to increase at the structural resonant frequency, since theoretically less applied force is required to
operate the device in resonance mode. By connecting an AC voltage to the drive electrodes, we started at a frequency 500 Hz below the theoretical resonance and slowly increased the frequency to 500 Hz above theoretical. Under close observation through the microscope, we were unable to detect any structural movement at any frequency. We predict that the drive force was not great enough to overcome the structural damping existing outside of vacuum.

The resonant mode would also be very difficult to physically observe because of the high frequency of very minute movements. Instead, the oscillations could be detected through the phase gain analyzer. The phase gain analyzer would sweep the drive electrode frequencies, while measuring the voltage output of a transimpedance amplifier connected to a changing capacitance. The resonant mode would then be indicated by an oscillatory voltage output. However, the sense electrodes surrounding the proof masses only see capacitive changes with orthogonal oscillations in sense mode. Therefore, we had no way to externally detect the drive resonance with the phase gain analyzer. We should have included an additional comb-fingered electrode between the two proof masses for external connection during testing.

The rest capacitance of the sense electrodes was an important parameter for classifying our readout circuit compatibility. Unfortunately, we could not form an external connection from any of the four pads to the LCR meter to make the measurement. A thin oxide is expected to have formed on the gold pads following fabrication, forming an insulating layer. It was necessary to first apply a small DC voltage between adjacent pads to break through the oxide before making measurements. However, the sense electrodes were isolated to single pads so we could not perform this necessary procedure. Because we have many unused pads, we should have dedicated two pads to each sense electrode, in which case we could have established electrical connection for making the measurements.

B. Drive Circuit Testing

To ensure Drive Circuit working capabilities we first started with testing our Operational Amplifier. Voltage offset was measured between the two inputs of the amplifier while being supplied Vdd and Vss. The voltage offset was measured at 55mV on the multi meter.

"Operational Amplifier"

The bandwidth was measured by finding the .707 Vmax of our signal at a frequency. The 3-dB frequency was measured to be 1.6MHz.

To ensure our Operational Amplifier is fast enough to track the 3.005kHz signal we need to measure Slew Rate. The Slew Rate was measured by applying a square wave and then finding the slope of the signal at the output in relation to the square wave input. The Slew Rate was measured to be 300mV/μs.

"Oscillator"

We tested the oscillator by applying Vdd and Vss separate from the operational amplifier. We measured the frequency at the output of the oscillator which serves as input to the operational amplifier.

Our expected signal was around 3kHz. In our lab measurements we obtained a frequency of 16kHz.

C. Readout Circuit Testing

Overall our readout circuit proved to be very difficult to test. One factor that caused this difficulty was that we only have each external connection connected to one pad. This did not allow us much freedom in testing as one bad connection
would result in an untestable die. As a result we were only able to test the op amp parameters as discussed in the Drive Circuit Testing section above. Our results gave us very similar values for the Slew Rate, Oscillation frequency, and Bandwidth.

Also in our testing sessions we found that the fabricated resistors within the readout circuit were slightly higher than expected. For R1 we got a resistance of 1.244 Ω instead of 1.044 Ω, and for R2 we measured 65.548 Ω instead of the theoretical 55.001 Ω. We believe this was caused by an actual sheet resistance higher than our estimate used in design calculation of 14.2 Ω/square. We investigate this sheet resistance in the next section using the test dies.

D. Test Dies

From our test session of the experimental test die we were able to estimate the value of the sheet resistance for our fabrication wafers. Using both the Poly-Si and Diffusion resistance values we measured we can find the sheet resistance of polysilicon and the Drain. Our measurements were 440 Ω for the Poly-Si resistor and 158 Ω for the Diffusion resistor. Using \( L/W = 416/16 \) for both resistors we can find both sheet resistances. The sheet resistance for Poly-Si turned out to be approximately 16.923 Ω and the sheet resistance of the Diffusion layer was 6.077 Ω.

E. Lessons Learned

Throughout the course of designing, fabricating, and testing our device, we learned several things and can suggest a few improvements on our work for the future. One important suggestion for future projects is that it is difficult to test some parts of the circuitry unless testing is kept in mind during the design phase. Including probe connections to certain test points in the circuit to important nodes in the circuitry is important to be able to test small sections individually. Another suggestion is for future groups to designate at least two pins at one node in fabrication. This is important because sometimes a layer of oxide forms on top of the pad and needs to be burned through to reach the actual connections to the probe. If there is only one pin per node, this becomes very difficult because the signal used to burn through must now travel through other parts of the circuitry, which could cause irreparable damage to the components.

X. SUMMARY

We have described a MEMS tuning-fork gyroscope comprised of two proof masses driven to resonance by interdigitated varying overlap comb fingers with DC and AC electric potential. The Coriolis-induced coupling between the two axes is detected by parallel plate capacitors. Additionally, the oscillations are mode-matched to the same resonant frequency for maximum sensitivity. The gyroscope is calculated to have a sensitivity of 0.011 mV/º/s. The ED-NMOS circuitry was also defined to generate the AC-signal to cause the drive oscillations, amplify the signal, and read-out the final capacitance change of the sense electrodes. Though some of the testing results were not as expected, this project was fruitful for learning. In the future, to create a better gyroscope, better fabrication methods would be used to create a stronger capacitive actuator to drive the mass. Additionally, the gyroscope would be tuned to a lower frequency and define testing methods while designing the device.

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