Design and Analysis of a Variable-Area Comb Drive Accelerometer for Parkinson's Tremor Data Collection

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***Abstract*—We propose a design of a Variable-Area Comb Drive Accelerometer used to collect data input from Parkinson's Patients. All design and analysis of the device is done through COMSOL, showing the viability of the device itself. Additionally, the microfabrication process flow of the device is shown with a potential way to etch silicon to achieve the designed accelerometer. The accelerometer COMSOL file can be found here: github.com/JohnDonahoe/ECE6200CombDriveAccelerometer.**

I. Parkinson's Disease Introduction

Parkinson's Disease is a relatively common neurological disorder that presents itself in multiple ways. The disease is a degenerative disorder, where its symptoms become worse over time. In the USA alone, it is estimated that 1 million people suffer from this disorder, with it being the second most common neurodegenerative disease after Alzheimer's disease [1].

The symptoms of the disease include tremors (generally in the hands/fingers and feet), slowed movements, poor balance and coordination, sleep disturbance and fatigue, and cognitive problems such as memory loss. The most prevalent symptom in Parkinson's is tremors, which is why most people know Parkinson's as the "disease that makes you shake".

Parkinson's is generally more likely to be diagnosed in those in the 65+ age range, with age being the primary risk factor. Men are also more likely to contract Parkinson's by around 1.5 times.

There is no specific known cause for why Parkinson's may occur, but is generally accepted that there are both genetic and environmental causes for the disease. According to Johns Hopkins Medicine, "individuals with a parent or sibling who is affected have approximately two times the chance of developing Parkinson's". Also, Johns Hopkins and other medical experts believe that exposure to toxic materials and pesticides may increase one's likelihood of Parkinson's. Lastly, it is believed that head trauma (whether repeated or one significant blow) may also increase likelihood.

There has been a significant increase in research into the causes and potential treatments for Parkinson's disease in the last 20 years, but it is unknown when or if the disease will/can be cured.

II. Parkinson's Tremor Dynamics

A. Tremor Locations

Parkinson's tremors can occur in many different parts of the body. They generally occur in the hands and fingers, but also may occur in the feet, face, and legs. Also, the tremors may be worse on one side of the body. These tremors can become worse with fatigue or stress, and are not always of equal intensities. They also are usually rhythmic, and occur both at rest and while doing something.

These tremors will cause Parkinson's patients to lose sleep, have worse handwriting, muscle stiffness, and other symptoms that are caused from the symptoms of tremors itself. Many scientific studies have been undertaken to find ways to soothe tremors in patients to allow them to live more normal lives, such as Deep Brain Stimulation. This technique involves surgically implanting a device in the brain to deliver electrical pulses into parts of the brain, reducing tremors by disrupting abnormal nerve signals.

While these techniques are effective in reducing the symptoms, Parkinson's is a degenerative disease that gets worse over time. There is only so much reduction in symptoms that is possible before a patient gets beyond helping. This disease, as well as diseases like Alzheimer's, continue to stump medical experts in finding specific causes, as well as finding total cures.

B. Hand and Finger Tremors

As the tremors are most likely to occur in the hands and fingers of a Parkinson's patient, that is what we will be designing our accelerometer to track. There have been various studies of the hand and finger tremors of Parkinson's patients, quantifying the tremors themselves. We will need to know the operating frequencies of the tremors as well as the acceleration range of the fingers that are caused by the tremors.

We will analyze the oscillatory frequency of tremors later in the paper when discussing the resonant frequency of the accelerometer. For now, the range of frequency that Parkinson's tremors occur in can be assumed to be between 3-12 Hz. This range is dependent on which type of tremor is specifically being tracked, but all are shown to be very close in frequency range.

To decide on a target range of acceleration to be tracked, we will be using a preexisting study on the tremors of Parkinson's patients.

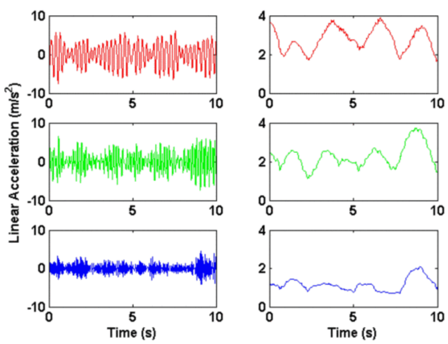

Fig. 1. Time series (left) of the 1st harmonic (red), the 2nd harmonic (green), and the 3rd harmonic (blue). RMS amplitude (right) of each harmonic calculated over the entire time span with a 1 second time window. (Y. Zhou et al. https://doi.org/10.1109/BHI.2016.7455922)

The upper-left graph in the figure above shows the acceleration characteristics of a Parkinson's patient. The acceleration is generally between -7 to 7 $\frac{m}{s^2}$, and while each tremor is not completely the same, the tremors occur in a very sinusoidal nature.

This will be important to take into consideration when designing an accelerometer to track Parkinson's patient tremors. We will want to design an accelerometer that is optimized for the -10 to 10 $\frac{m}{s^2}$ range, that is capable of sensing high resolution acceleration changes.

III. Accelerometer Design Choices

A. Single Cantilever vs. Comb Drive

Single-Cantilever and Comb-Drive Accelerometers are two distinct types of MEMS devices, each with its own advantages, disadvantages, and process flows. Single-Cantilever Accelerometers are more simple to conceptualize, while Comb-Drive usually require the usage of complex simulation software to find behavior and characteristics.

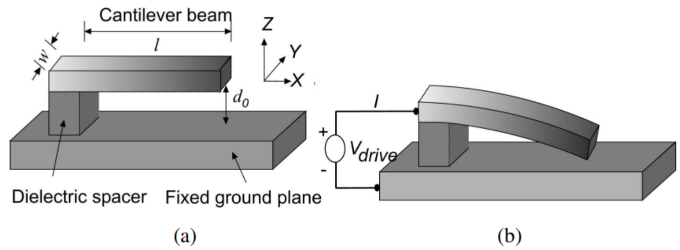

Fig. 2. Cantilever with applied electricity to create capacitive force.

Pictured above is a single cantilever-beam structure. This design is relatively easy to mathematically compute behavioral characteristics, although we will not go into that. A cantilever-based accelerometer tracks vertical acceleration, that can be most easily described as diving board-like movement.

At rest, the cantilever is flat and holds a certain capacitance between the conductive fixed plate below it. The bottom of the cantilever is treated as one plate, and the top of the fixed ground plate is treated as the other. The capacitance of the two plates is calculated using the equation below:

$$C = \frac{\epsilon_0 A}{d} \tag{1}$$

The variable ϵ_0 is considered the permitivity of the space between the plates, which is a constant. The variable A is the overlapping area of the two plates sharing a capacitance charge, and the variable d is the distance between the plates.

When an acceleration occurs upwards (in the Y direction) of the cantilever, the overhanging structure will bend downwards (similar to (b) in Fig 2). As the distance between the plates decreases due to the bending, the overall capacitance of the system increases. Likewise, an acceleration downwards will cause the structure to bend upwards, increasing distance and decreasing capacitance.

By tracking the capacitance between the two plates, the acceleration of the system can be estimated to a decent degree. Note that a moving system at constant velocity (no acceleration) will not cause the cantilever to bend, there must be an acceleration in its designed direction.

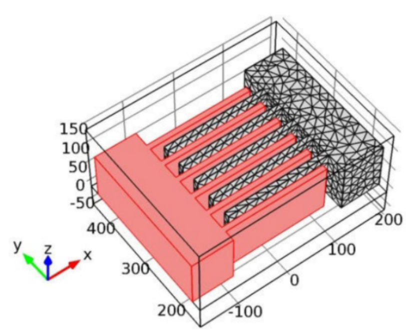

Fig. 3. COMSOL model of a parallel plate comb structure.

Pictured above is a parallel plate capacitance comb-like structure, which can be utilized to create what is known as a "Comb Drive Accelerometer". These tend to be much more accurate than a single cantilever structure, but are more complex to analyze as well as etch/produce.

There is an overall increase in the total capacitance of the system, as the plates produce capacitance on both sides. Any change in the system, such as the red comb from above moves in the negative x direction, or in the y direction, will change the capacitance of the system.

B. Variable Gap vs. Variable Area

The two different types of Comb-Drive Accelerometers we had the option to choose from are pictured below:

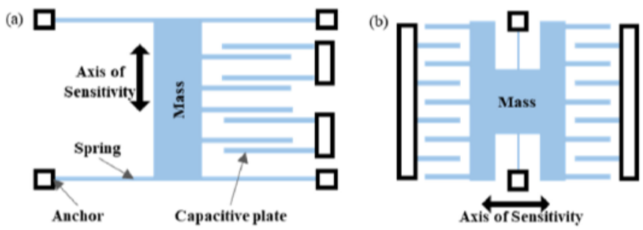

Fig. 4. Two different Comb-Drive accelerometers, (a) being a Variable Gap and (b) being Variable Area. Both are capacitive-based accelerometers. (Tao, Q. et al. https://doi.org/10.3390/s23031568)

This figure shows a very simplistic representation of Comb-Drive accelerometers. The pieces attached to the anchors (white squares) are floating and are movable, while the plates attached to the walls (white rectangles) are not intended to move and may be attached to the floor.

The left figure (Fig 4.a) shows a variable-gap accelerometer. This operates by the mass moving in either direction of its axis of sensitivity (shown in the figure) when an acceleration force is applied to the whole system. When an acceleration is applied, the plates connected to the center mass will either get closer to the plates attached to the walls (increasing capacitance) for further from (decreasing capacitance).

The right figure (Fig 4.b) shows a variable-area differential accelerometer. When an acceleration force is applied in the axis of sensitivity, one set of plates will increase in capacitance and the other set will decrease in capacitance. Further explanation into differential capacitance will be shown later.

While the figure is simplistic drawing of what these accelerometers can look like, much can be learned from it. Both of these comb-drive accelerometers will have a significant more amount of plates being tracked as compared to the simple cantilever design. This will allow for greater sensitivity, and likely less voltage is able to be applied to see an acceleration applied.

C. Size of Accelerometer

For our goal, we did not have a highly specific size requirement necessary for the accelerometer. Generally, the smaller the accelerometer the better, so long as it fulfills your necessary goals. A smaller accelerometer may be harder to manufacture, however, so there needs to be a balance between size.

D. Material for Accelerometer

Accelerometers are designed with multiple characteristics in mind that the material has an effect on. These are, while not limited to, conductivity, fabrication compatibility and complexity, and mechanical stability. Generally, accelerometers are designed to be created using Silicon (either single-crystal or Polysilicon), as it is conductive and rigid. It is also easy to fabricate using an extremely large number of etching techniques.

Other materials can be used in the design or as sacrificial materials in the etching process. Doping silicon plates with metals can increase the capacitance of the device, and in some fabrication techniques Silicon Dioxide may be used sacrificially to etch specific structures and create overhangs.

E. Differential Sensing Scheme

There are various ways to implement a comb-drive accelerometer, one of which being a non-differential or a differential plate drive. A differential plate drive accelerometer describes a design in which the displacement (and thus acceleration) is calculated by measuring one side of plates capacitance, and subtracting another side of plate capacitance. A non-differential describes a design in which you are simply measuring one set of plates total capacitance.

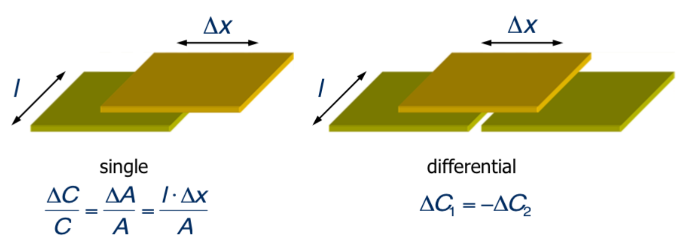

Fig. 5. Single plate vs. differential plate capacitance models.

Although our end-design will not look quite like this, the concept is the same. One version measures one set of plates, and the other measures two sets of plates and subtracts one value from the other. The technique of a differential accelerometer is useful in scenarios where the environment is not perfect. Any electrical noise from the environment or weak grounds to the plates themselves can affect the total capacitance readout values. By differencing the capacitance values on both sides, it will fix this issue for the most part.

While this may not be the most necessary design consideration for tracking Parkinson's patients tremors, it allows our design to operate in a greater target of precision.

F. Resonant Frequency Target

The operating frequency of our testing must be far below the resonant frequency of the accelerometer itself in order to keep the results as accurate as possible. All devices and physical structures have natural frequencies, that if subjected to this frequency, demonstrate a significant change in their physical characteristics. Buildings subjected to earthquakes that vibrate in their natural frequency may fall over.

Any accelerometer operated close to or at its natural frequency will produce greatly inaccurate results. This resonance is not desirable, so it is necessary to create a device with a resonant frequency much higher than that of its target operating frequency. For Parkinson's tremors, the "classical rest tremor, isolated postural tremor, and kinetic tremor during slow movement have been reported as 3-7 Hz, 4-9 Hz, and 7-12 Hz, respectively" [2]. This means our target resonant frequency should be much higher than 12 Hz, so we decided to target around the 100-1000 Hz range.

A resonant frequency that is much larger than that range may mean the structure is very rigid, and the change in plate capacitance for a given acceleration is extremely low. This would require highly precise capacitance sensing circuitry, which can be difficult and/or expensive. By treating the accelerometer as a simple spring-mass system, we can use the equation below to find resonant frequency:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2}$$

The variable k is the stiffness of the spring, and m is the mass of the object. By increasing mass, we make the device more sensitive to change, but also reduce the effective range of frequencies the device can measure.

G. Capacitive Plate Count and Size

The plates attached to the moving mass, as well as the fixed plates attached to the walls, are not required to be of any specific size. There is also no requirement for the number of them, but there are specific principles that need to be followed to design a comb-drive accelerometer to fit your needs.

By adding more plates to the system, there will be a larger capacitance held between all plates combined. This will allow for a system that has high capacitance at rest, and when acceleration occurs, the change in capacitance will also be higher, allowing for more precise acceleration approximation.

With taller and larger plates in the system, the plates will have both more area overlapping and less distance between the plates, which will increase total system capacitance. The same properties from above will benefit the device as well.

With a greater number of plates and larger plates, the total device mass will increase, which causes the system to produce a greater displacement when subjected to acceleration. The system needs to be tuned with a specific acceleration range to ensure the highest resolution of detectable change. With the increase in mass, however, structural analysis of the system will need to be calculated to ensure the accelerometer will not break in its peak operating range.

H. Off-Axis Sensitivity

Our accelerometer design is looking to track acceleration in one axis only. Accelerations in any other axes need to affect the capacitance readout as little as possible, to ensure the device is getting accurate measurements. We must design the system to be flexible in one axis, and in the other two it must be rigid.

IV. Our Design

Our team decided to model a Variable-Area Comb Drive accelerometer, as we believed it would be more accurate in its measurements due to the differential-capacitance nature of the design.

A. Iterations of Design

We began with a naive approach by simply creating a model that was a near one-to-one representation of the design in Fig 4b. As none of the members of our group had experience designing MEMS devices, we felt that starting here was a good baseline.

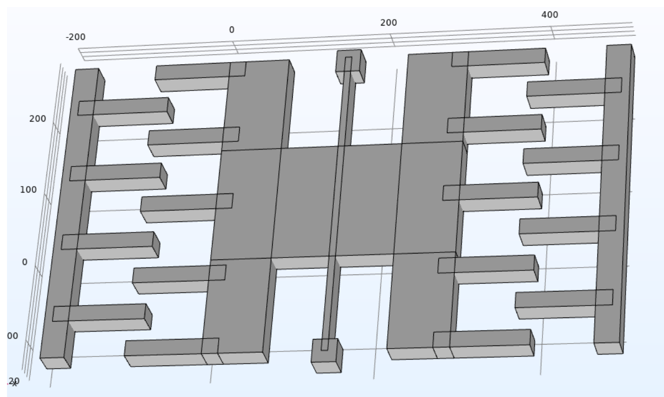

Fig. 6. Iteration 1 of a Variable-Area design.

Figure 6 is a screenshot of the original device we made. As you may observe, it is a very basic design that does not have many capacitance plates. We set up all of the fixed points and moving figures off of this design, which allowed us to see where we needed change.

This initial iteration proved to be extremely rigid, and the plates were not close enough to create a noticeable capacitance charge. Also, we noticed that if the device were to move in the vertical direction ("in" and "out" of the screen from this view), the capacitance would also change which is not ideal.

In the next iteration, shown in Figure 7, we increased the thickness of the moving device itself which served two purposes. The first purpose was to increase the mass of the device, which would increase displacement. The second purpose would be to minimize the effect of the vertical acceleration displacement vs capacitance readout. In this design, if there were to be a significant vertical acceleration, the overlapping area of the plates would not change. Because of this, capacitance would not change.

The next iteration, shown in Figure 8, had us increasing the length of the spring and dramatically increasing the number of

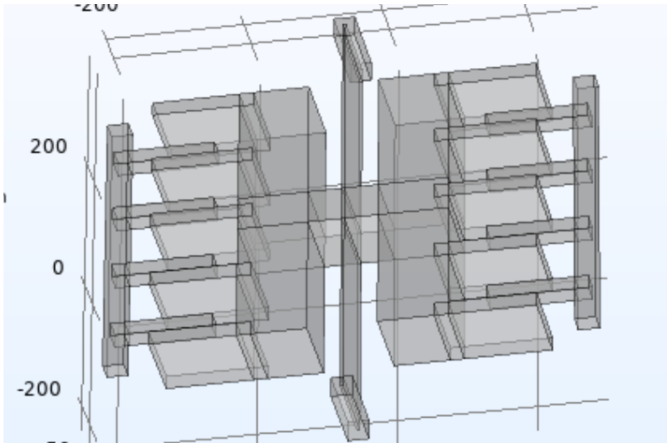

Fig. 7. Iteration 2 of a Variable-Area design.

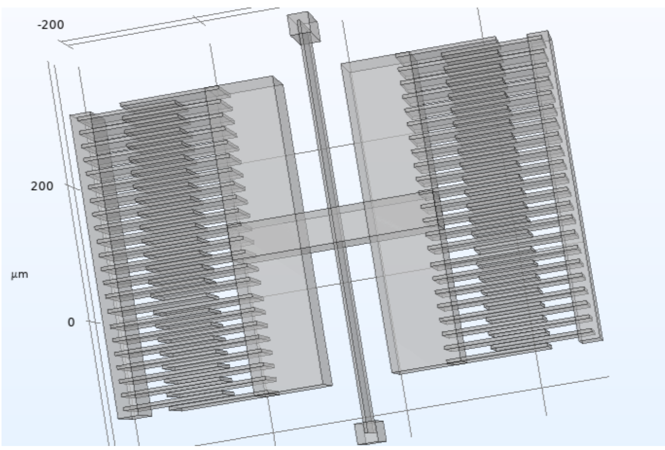

Fig. 8. Iteration 3 of a Variable-Area design.

plates. All changes made here were to increase the displacement of the device, and increase the total capacitance of the device as well. We tested many variations of the center proof mass thickness to see if there was a sweet spot between length of spring and mass of the system.

The fourth iteration of our design, shown in Figure 9, saw an increase in the thickness of the center mass, increase in thickness of all plates, and an increase in length of the plates extending from the center mass.

Our final iteration of the design is shown in Figure 10. Between iteration 4 and now, we almost tripled the number of plates and also decreased the overall thickness of the device. With this, we also increased the length of the spring to be much longer than before. At this point, the device has a total thickness of 50um, and the gaps between the fixed plates and moving plates are 1um. This allows us to use a DRIE process to etch the accelerometer.

The center movable mass has a voltage of 0V, and the fixed outer walls and plates have a voltage of .1V. The entire device is polysilicon.

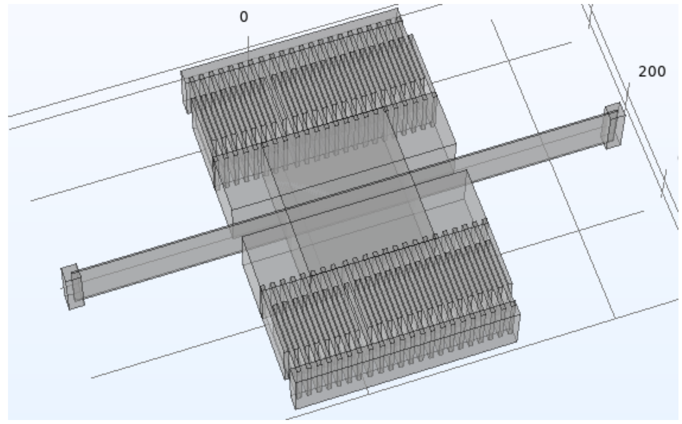

Fig. 9. Iteration 4 of a Variable-Area design.

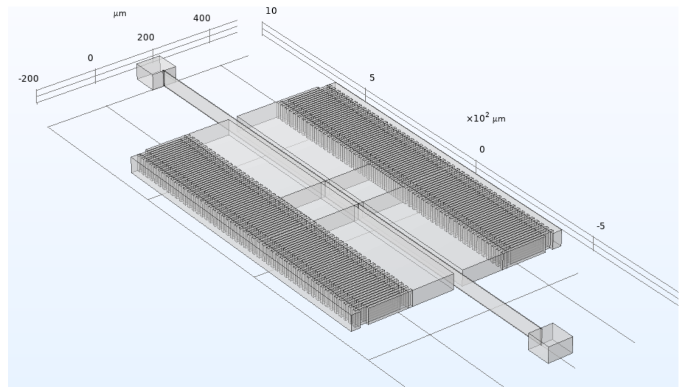

Fig. 10. Final iteration of a Variable-Area design.

B. Problems Arisen in Design

In the process of creating the accelerometer, we noticed that the polysilicon spring coming from the fixed anchors forced the system to be extremely rigid. Through testing, we noticed that polyimide would serve as a "perfect" replacement to dramatically increase the displacement. The issue with this, however, is that polyimide is not conductive, and the process flow to create a polyimide-based spring system would not be very possible. Because of this, we had to find other ways to increase the displacement of the system.

V. Testing and Simulation Results

A. Acceleration and Capacitance (Sensitivity and Resolution)

The resolution of our device allows us to see around .01G of force per femtofarad of change. The true value of estimating 1 m/s^2 is 9.7fF of change. The capacitance simulated change function is shown here:

$$y = 8.84x - .565 \tag{3}$$

With x being acceleration and y being capacitance in fF. When solving for x, we can approximate the transfer function of the device to accurately estimate acceleration. In the

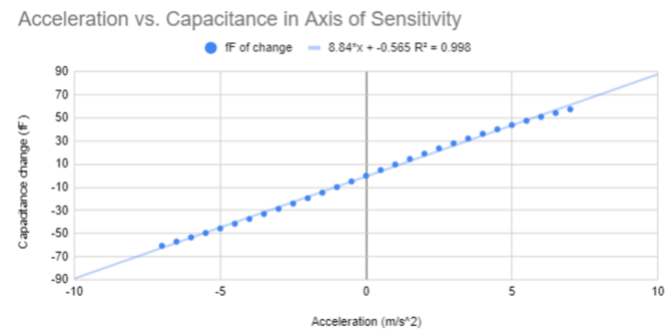

Fig. 11. Applied Acceleration vs. Change in Capacitance.

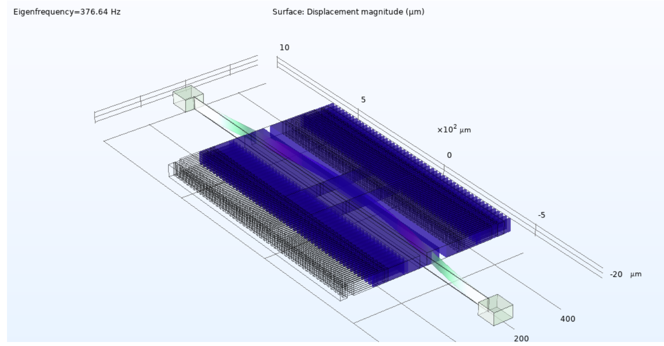

Fig. 13. Natural Frequency of the device in the axis of sensitivity.

simulation, we treat acceleration as the known variable, and are solving for capacitance. In the real world, we will know the capacitance through a readout circuit, and will use that to solve for estimated acceleration. The transfer function is shown here:

$$x = \frac{y}{8.84} + .064 \tag{4}$$

In the readout circuit specifications described by Elmala et al., their circuit achieved a sensitivity of 35 fF/g or 3.57 fF/(m^2/s) [5]. Our accelerometer provides a sensitivity of 86.632 fF/g or 8.84 fF/(m^2/s), which is sufficient to fit within the sensitivity range of the circuit described above and modern readout circuits. Although more advanced accelerometers can detect μg resolution, our target was to detect 1 fF/0.1 (m^2/s) for a resolution of 0.1 m^2/s or 0.98 g. To achieve more specific or higher resolution, more information about our accelerometer's capacitive noise floor and the readout circuit would be necessary, however, this lies outside of the scope of our project.

B. Dynamic Range

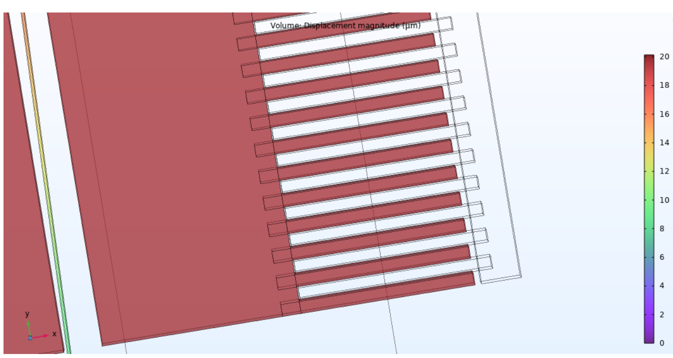

Fig. 12. Dynamic Range of device limited by fixed plates.

With an applied force of around 500 m/s^2, the plate ends begin to collide. This will define our maximum dynamic range between -500 to 500 m/s^2.

C. Resonant Frequency of the Accelerometer

Using the COMSOL built-in Eigenfrequency studies, we are able to approximate the natural frequency of the device in its axis of sensitivity. The study approximates the natural frequency of the device at around 377 Hz. Given that the frequency of Parkinson's tremors are generally characterized to be between 3-12 Hz, this is more than enough of a buffer to ensure optimal accelerometer operating ability.

D. Off-Axis Sensitivity

accTremor (m/s^2)	Left Plate (fF)	Right Plate (fF)	Left minus Right (fF)	Left minus right norm (fF)
-7.0000	5645.4	5635.4	9.9852	-0.062812
-1.5000	5645.4	5635.4	9.9804	-0.067649
-1.0000	5645.4	5635.4	9.9933	-0.054710
-0.50000	5645.4	5635.4	9.9955	-0.052494
0.0000	5645.4	5635.4	9.9969	-0.051114
0.50000	5645.4	5635.4	9.9982	-0.049798
1.0000	5645.4	5635.4	9.9995	-0.048488
1.5000	5645.4	5635.4	10.001	-0.047179
7.0000	5645.4	5635.4	10.002	-0.045872

Fig. 14. Y-Axis capacitive change based on acceleration.

accTremor (m/s^2)	Left Plate (fF)	Right Plate (fF)	Left minus Right (fF)	Left minus right norm (fF)
-7.0000	5645.4	5635.4	10.010	-0.037822
-1.5000	5645.4	5635.4	10.007	-0.041432
-1.0000	5645.4	5635.4	10.000	-0.047946
-0.50000	5645.4	5635.4	9.9995	-0.048536
0.0000	5645.4	5635.4	9.9989	-0.049114
0.50000	5645.4	5635.4	9.9983	-0.049692
1.0000	5645.4	5635.4	9.9977	-0.050269
1.5000	5645.4	5635.4	9.9972	-0.050848
7.0000	5645.4	5635.4	9.9966	-0.051430

Fig. 15. Z-Axis capacitive change based on acceleration.

To confirm minimal sensitivity along the off-axis directions, we applied up to $7 * 0.1 * 9.81 m/s^2$ accelerations in both the y and z axes. As shown in our simulation plots, the resulting change in capacitance (ΔC) remained negligible throughout the entire test range, even at our devices maximum rated acceleration. These findings confirm that our device exhibits minimal response in the y and z directions—meaning off-axis motion does not interfere with primary-axis measurements—validating the low off-axis sensitivity of our accelerometer design.

Figures 14 and 15 show the applied accelerations in both axes not on the axis of sensitivity (defined in our case as the X-axis) and the resultant changes in capacitance. This ensures the only acceleration direction that can affect our readout circuitry is the direction we want.

VI. Fabrication Process Flow

A. Introduction

The device is fabricated using polysilicon as the accelerometer material and gold as the fixed electrode for connection to the sensing circuit. The process flow incorporates several key techniques, including wafer bonding, photolithography, metal deposition, deep reactive ion etching (DRIE), and the use of a sacrificial oxide layer to release the free-hanging structure. The design process draws inspiration from the work of Liu et al [4]. The fabrication flow follows established MEMS methods to achieve precision and repeatability.

B. Material Selection Test

The materials were chosen for their mechanical stability, electrical conductivity, and compatibility with fabrication technology:

- **Polysilicon:** Provides mechanical strength, thermal stability, and compatibility with MEMS fabrication.
- **Silicon Dioxide (SiO_2):** Acts as a sacrificial layer and electrical insulator. It is grown through thermal oxidation.
- **Gold (Au):** Used for high conductivity for the fixed electrodes in connection to the readout circuit.
- **Chromium (Cr):** Applied as an adhesion layer to improve gold bonding to polysilicon.
- **Negative Photoresist:** Used for photolithography patterning and etching masks.

C. Fabrication Steps

1) Polysilicon Wafer Preparation: A polysilicon wafer substrate (500 μm thick) is selected to attach our accelerometer. The wafer should be cleaned in a piranha solution like (H_2SO_4:H_2O_2) to remove organic contaminants.

2) Silicon Dioxide Growth: A thermal oxidation process is performed at high temperatures around (1100)°C using dry oxidation to grow a SiO_2 layer (1–2 μm thick). This layer serves as a sacrificial oxide for later release of the structure and serve as an electrical insulator. The diagram in Fig 13 (2) could have an Oxide layer on the bottom side of the wafer, but this will not affect our process flow as the oxide layer will be etched away at the end.

3) Wafer Bonding: The oxidized wafer is bonded to another polysilicon wafer (50 μm thick) using direct wafer bonding. The wafers are brought into contact and annealed at 1100°C to form the bond, resulting in an oxide layer sandwiched between two polysilicon layers.

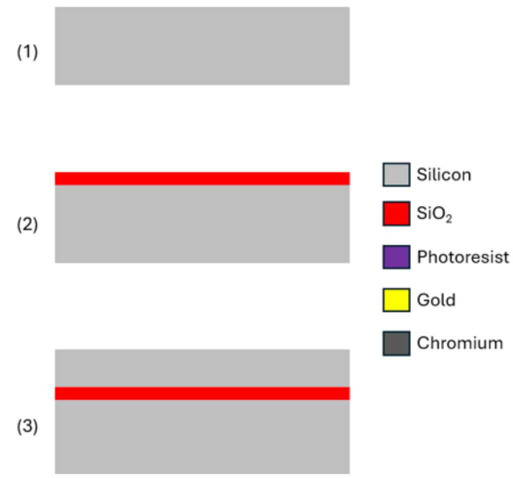

Fig. 16. Steps 1-3 for wafer bonding

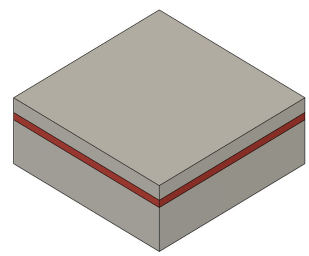

Fig. 17. 3D model of oxide layer sandwiched between polysilicon layers

4) Mask for Metal Deposition: Photoresist is spin-coated (1-2μm thick) and patterned via photolithography to define the electrode regions where the Au and Cr layers will be deposited.

5) Metal Deposition for Fixed Electrodes: A thin layer of Cr (10-20 nm) is deposited, followed by Au (200–300 nm) using electron-beam evaporation as a physical vapor deposition (PVD) method.

6) Lift-Off Process: The wafer is immersed in acetone, dissolving the photoresist and removing unwanted metal.

7) Patterning for DRIE: A second photoresist layer (2–5 μm thick) is applied, and photolithography is used to define the accelerometer's structure on our top polysilicon layer.

8) Deep Reactive Ion Etching (DRIE): The Bosch DRIE process etches through the top polysilicon layer (50 μm deep for accelerometer depth) to carve the device structure. The alternating cycles of SF_6 for etching and C_4F_8 for passivation ensure high aspect ratio sidewalls for our capacitors.

9) Photoresist Removal: The remaining residual photoresist is removed by immersing the wafer in acetone.

10) Sacrificial Oxide Removal: The structure is immersed in HF to selectively remove the SiO_2 layer, releasing the free-hanging accelerometer structure.

D. Design Considerations

Several key design choices were made to optimize fabrication and device performance:

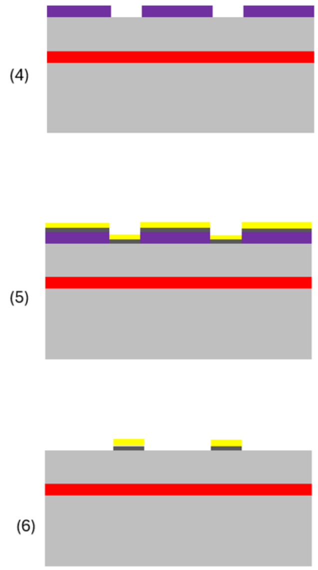

Fig. 18. Steps 4-6 for adding the Chromium and Gold layers

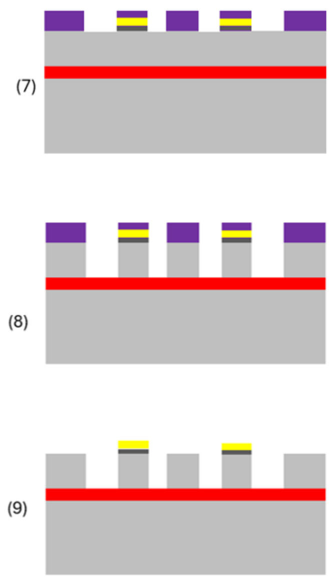

Fig. 19. Steps 7-9 for DRIE

- **Polysilicon for Structural Elements:** Polysilicon was selected over other materials such a monocrystalline silicon due to its rigid mechanics.
- **Silicon Dioxide as a Sacrificial Layer:** SiO_2 was chosen for its precise growth control and selective etchability using HF without damaging the other materials.
- **Cr/Au for Electrodes:** Chromium was used as an adhesion layer to improve gold bonding to polysilicon because gold has poor adhesion.
- **E-Beam Evaporation for Metallization:** This method ensures high-purity, uniform metal deposition, avoiding conformal coating that the sputtering technique produces.
- **Lift-Off vs. Wet Etching for Metal Patterning:** Lift-off was preferred as it provides cleaner mask patterns and avoids having gold on unnecessary surfaces.
- **Wafer Bonding Order:** Oxide was grown before bonding to ensure electrical isolation and maintain a gap for the accelerometer to stay suspended in air.
- **DRIE for High Aspect Ratio Features:** The Bosch DRIE process was used to create the vertical sidewalls in the comb structure.
- **HF Release Etch:** HF removes the unwanted SiO_2 without reacting with any other material on the device.

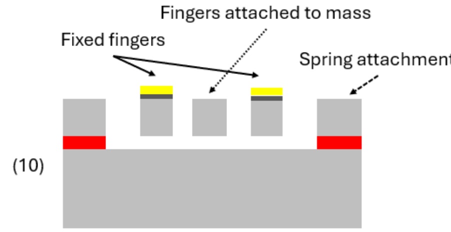

Fig. 20. Final wafer cross-sectional view after oxide removal

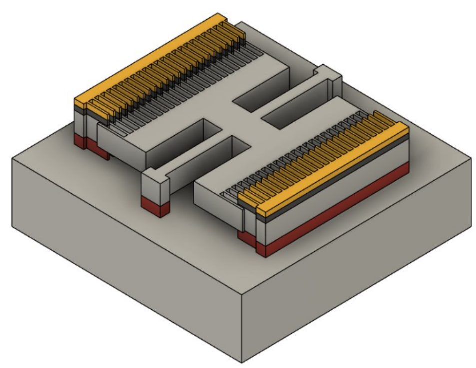

Fig. 21. 3D model of the final wafer

VII. Out of Scope Considerations

A. Physical Packaging of the Die

For this project, we were tasked with designing and simulating a Comb-Drive Accelerometer in the COMSOL software, as well as creating a fabrication process to etch the device from a wafer of a chosen substance. We were not tasked with actually fabricating the device and designing a way to package it into a total chip.

A few assumptions were made in our design of the chip, one being that the accelerometer would operate in air, as opposed to a vacuum. We made this assumption as it allowed for an easier fabrication process flow. We ran all simulations in COMSOL with it in air.

Also, we were not tasked with creating a capacitance readout circuit for the device. We simply created a process flow that allows us to connect it to a pre-built readout circuit.

VIII. Conclusion

A. Findings

Through our design and simulation process, we developed a Variable-Area Comb Drive Accelerometer optimized for tracking Parkinson's tremors. Our COMSOL simulations confirmed that the device successfully operates within the target frequency range of 3–12 Hz while maintaining a natural frequency of approximately 377 Hz, ensuring stable operation without natural resonant frequency interference. The design demonstrated a dynamic range of ±500 m/s^2, although it was optimized for the ±10 m/s^2 range. The material selection of polysilicon, silicon dioxide, and gold proved compatible with the fabrication process, which ensured a relatively simple fabrication process flow. The accelerometer's design, featuring a differential capacitance sensing scheme and variable-area configuration, enhances sensitivity, which makes it optimal for tracking the small range of acceleration that Parkinson's tremors create.

B. Challenges

The project presented several challenges, beginning with the steep learning curve associated with COMSOL's FEA capabilities. We spent significant time understanding the software's CAD designing and simulation tools. Most of our challenges were because our device's displacement was not high enough, which meant too little of change in capacitance. Material selection posed another obstacle, particularly when considering polyimide for increased flexibility, but since it is not conductive we could not use it. Finally, ensuring minimal off-axis sensitivity required careful tuning of the device geometry to maintain directional accuracy.

C. Future Direction

Future work could focus on actually fabricating a physical prototype based on the proposed design to validate the simulated results. COMSOL is a very robust tool, but without actual validation, we cannot be 100 percent sure of our design. Although the capacitance sensing circuit was out of our scope for the project, there may be a potential for integrating the accelerometer with a custom-designed capacitive sensing circuit to further optimize resolution. Also, the device packaging being outside the scope of our project meant we did not have to simulate environmental changes that may affect capacitance readouts. These are things like humidity that can modify capacitance. More work is necessary to ensure the device we made is actually fully operable.

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