Design and Fabrication of a Three-Axis Capacitive Accelerometer

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***Abstract*—This paper focuses on the design and fabrication of a surface MEMS three-axis accelerometer with comb-drive fingers that measures acceleration up to 10G in the x/y-direction, and 5G in the z-direction on a single device using capacitve sensing. The fabrication process was performed in the Semiconductor and Microsystems Laboratory (SMFL), with a 7 level process flow to achieve the desired features. The accelerometer was designed to have a movable top electrode with sensing fingers attached to it to sense the change in capacitance the x/y-direction and a bottom electrode to sense the change in z-direction. The paper will focus on the design, fabrication, and resulting defects that affected the device.**

***Index Terms*—MEMS, Accelerometer, Displacement, Capacitance, Comb-Drive, Sensing Fingers, Fabrication**

I. INTRODUCTION

THE introduction of microelectromechanical systems (MEMS) in the 1980s has gain huge popularity and has been implemented into many of the devices used today such as phones, game controllers, car airbags, and many other useful applications. MEMS devices have mechanical and electrical properties and are created using microfabrication processes. Since these devices are able to be fabricated on a silicon substrate, it has made the it was very easy to integrate and manufacture in the industry. The accelerometer is a specific MEMS device that is used to measure the change in acceleration due to the change in force applied to the device.

The three-axis accelerometer and comb-drives have not been successfully fabricated in the SMFL. The purpose of this project was to address both of these problems. The movable proof-mass will be fabricated on top of a sacrificial layer called Tetraethyl Orthosilicate(TEOS). The release of this device has been one of the hardest and crucial processing step. This paper will focus on the design and fabrication of a surface MEMS three-axis accelerometer with comb-drives to measure acceleration in laterial and vertical directions.

II. THEORY

A. Mechanical Theory

The accelerometer comprises of a square proof-mass with fingers attached to it on all four sides. When designing the device, there are parameters to consider that will affect the displacement of the device.

Force applied on the device is what allows the device to be displaced. According to Equation [1], the mass of the device plays an important role for the accelerometer. For acceleration in terms of G's, it is simply the multiple of the force of gravity. For example, acceleration of 2Gs would be two times 9.8. When designing the accelerometer, it is important to understand some mechanical fundamentals such as force and spring constants. The equation below is the equation for Force. [3]

$$F = ma \tag{1}$$

$F =$ Force (N) , $m =$ Proof of mass (kg)
$a =$ Acceleration (m^2/s)

The beam springs are used to displace the proof-mass as the force is applied to the device. These springs constants, also known as stiffness constant, is used for the displacement. The common equation for the force and spring constant is rearranged to find displacement.

$$F = -kd_o \tag{2}$$

$$d_o = \frac{-F}{k} \tag{3}$$

$F =$ Force (N) , $k =$ Spring Constant (N/m)
$d_o =$ Displacement (m)

The spring constant of the crab-leg design uses equal length of the shin and thighs for a simpler model in the following equation. [1]

$$k_{xy} = \frac{EH_bW_b^3(5L_b)}{L_b^3(2L_b)} \tag{4}$$

$$k_z = \frac{48EH_bW_b^3}{L_b^3} \tag{5}$$

where:
$k_{xy} =$ Spring Constant in X/Y Direction
$k_z =$ Spring Constant in Z Direction
$E =$ Young's Modulus
$H_b =$ Height of Beams
$W_b =$ Width of Beams
$L_b =$ Length of Beams

The spring constant of the X/Y and Z direction was calculated to be 3.48 N/m and 66.8 N/m, respectively.

B. X/Y-Directional Comb-Drives

One period of the comb-drives is made of one movable finger in-between two fixed fingers with a small gap (d_o)

between each fixed finger. The total capacitance of the fixed fingers is found in the following equation.

$$C(fingers) = (\frac{\epsilon_o \epsilon_r N_s L_s H_s}{d_o}) * (\frac{1 + d_x}{d_o}) \quad (6)$$

where:
ϵ_r = Relative Permitivity
ϵ_o = Permitivity of Space
N_s = Number of Sensing Fingers
L_s = Length of Sensing Fingers
H_s = Height of Sensing Fingers
d_o = Finger Gap
d_x = Displacement of Sensing Fingers

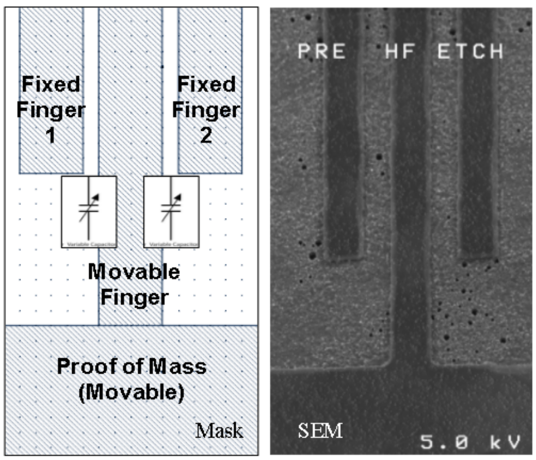


Figure 1: Top-down view of the fixed and movable fingers from the mask design.

As the movable finger displaces away from a fixed finger, it decreases in capacitance while increasing capacitance to the other fixed finger [2]. The more fingers on the proof of mass will allow for more change in capacitance sensing so it is best to have as many fingers as possible on each side of the square proof-mass. The square of mass size is chosen to be $1500\mu m$ by $1500\mu m$, with $4\mu m$ by $4\mu m$ holes across the entire square. There is a total of 296 fingers on the device with 74 fingers on each side. These fingers will also increase the weight of the proof-mass as more fingers are added, increasing the sensitivity of the device. The total weight of the device comes out to be $9.04\mu g$.

C. Z-Directional Parallel Plates

The Z-direction of the accelerometer comprises of the top electrode, which is the movable proof-mass, and a bottom electrode for sensing. The bottom plate electrode was designed to be $1000\mu m$ by $1000\mu m$. The change in capacitance as the distance between the plate changes from displacement can be seen from the equation below.

$$C_z = \frac{\epsilon_o \epsilon_r A}{d_o} \quad (7)$$

A = Area of Bottom Plate

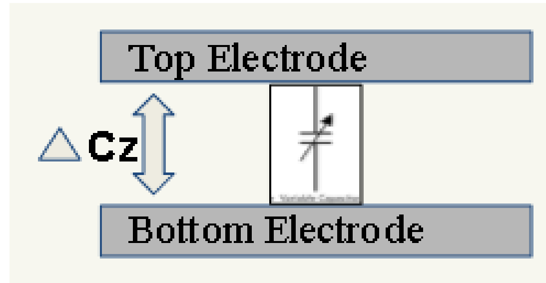
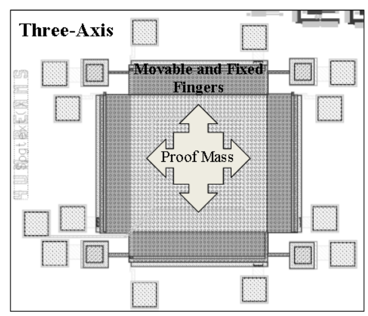


Figure 2: Cross-Section of the device with Top and Bottom electrodes.

D. Device Parameters

Taking in the considerations of the design of the fingers and top/bottom electrodes, the design of the three-axis accelerometer was made.



(a)

Parameter	Measurements & Units
Proof Mass Size	1500μm x 1500μm
Proof Mass Thickness	2μm
Proof Mass Weight	9.04μg
Comb Finger Gap	1μm
Comb Finger Length	200μm
Beam Length	250μm x 250μm
Beam Width	4μm

(b)

Figure 3: (a)The mask design of the device. (b) The parameters of the device.

III. Simulations

. The simulations of the device was designed on ANSYS 18.1 to extract the linear relationship of displacement with force. The X/Y and Z direction was simulated individually using ANSYS Workbench.

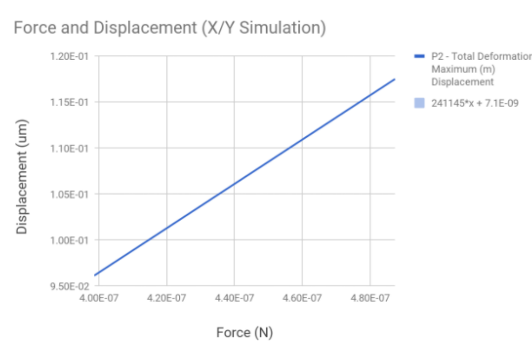


Figure 4: The extracted linear relationship of displacement and force in the laterial (X/Y) direction from ANSYS Workbench

Figure 5: The extracted linear relationship of displacement and force in the vertical (Z) direction from ANSYS Workbench

Using the extracted linear relationships above, the change in capacitance can be simulated using the equations from the design of fingers.

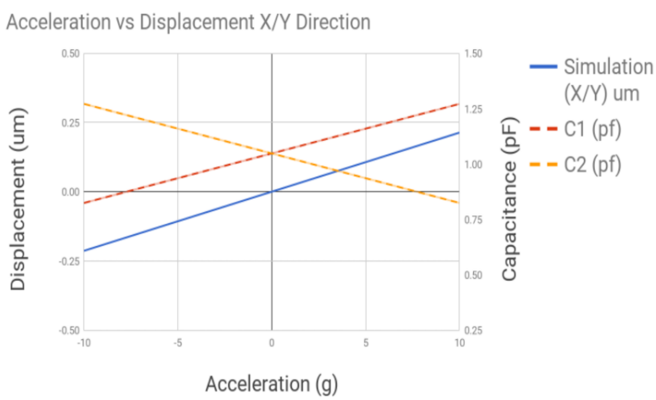


Figure 6: The change in displacement and capacitance with the change in acceleration in the laterial (X/Y) direction. The device is operational within $\pm$ 10G that allows the displacement to be within 20% of the finger gap.

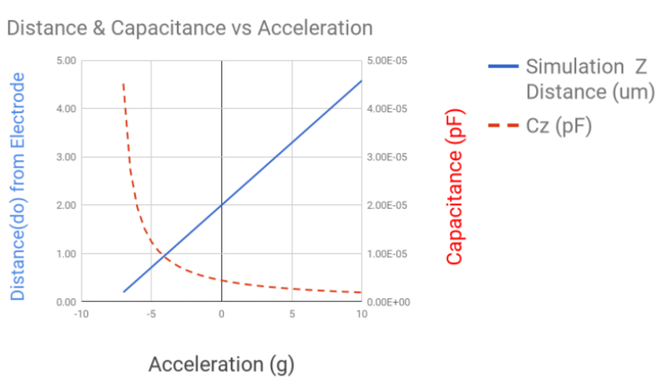


Figure 7: The change in displacement and capacitance with the change in acceleration in the vertical (Z) direction.The device was designed to operate only at $\pm$ 5G due to the 2μm sacrificial layer of TEOS.

IV. Fabrication

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A. Process Flow

The entire fabrication is done on a (100) p-type Si wafer and is all completely done in the SMFL. The fabrication of the device consists of the 7 level process flow.

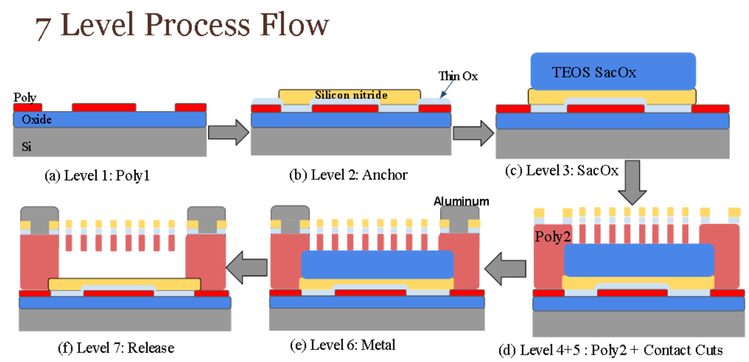

Figure 8: The mask design of the die used for fabrication with single,dual, and three-axis accelerometers

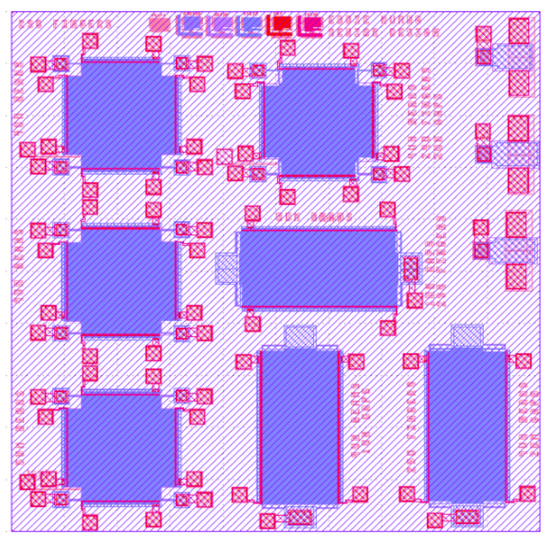

Figure 9: The mask design of the die used for fabrication with single,dual, and three-axis accelerometers

The first level of the fabrication consists of the field oxide and a patterned poly-silicon layer for the bottom electrode. The oxide was grown in the Bruce Furnaces and the poly was deposited in the low-pressure chemical vapor deposition (LPCVD). The poly was grown to be about $0.71\mu m$ and then doped using spin-on-dopants (SOD). The sheet resistance was not uniform, varying from 450-2000 ohms/sq.

The second level is the anchor for connection of the poly1 and poly2 layer. The silicon nitride layer was grown first to be about $0.4\mu m$, and then etched down to the oxide.

The third level is the patterned 2μm of TEOS that was deposited using the AME P5000. The TEOS is used support the deposition of the poly2 layer and will be released in

the further processing steps. The TEOS was defined using a Buffered Oxide Etch (BOE) 5:2:1 until the poly was exposed.

The fourth level consists of the top electrode, poly2 layer, that will be the defining layer for the movable mass. This is the critical layer because this is the patterning of all the spring beams, fingers gaps, and etch holes. The poly was doped using SOD, with sheet resistance of 30 ohms/sq.

The fifth level is the patterning of the contact cuts for metal connections. This level is necessary to etch through the silicon nitride and pad oxide to make electrical connections to the poly.

The sixth level is the metal patterning of the aluminum. The 99% aluminum and 1% silicon is deposited using the CVC601 DC sputtering system in the SMFL. The power was 2000W, pressure was pumped down to 3E-6 torr, and deposited for 34 minutes. The target thickness was $1\mu m$.

And finally, the seventh level is the release of the device by etching the TEOS. The release is the last critical step to the process. The poly2 square proof-mass was designed to have 34,225 $4\mu m$ by $4\mu m$ holes spaced by $4\mu m$ from each other. The release process is the TEOS is being etched by the Buffered Oxide Etch 5:2:1, where the BOE will etch $2\mu m$ in an isotropic direction, clearing out the etch holes and the spacing between the holes.

B. Fabrication Defects

The process flow had many fabrication defects that prevented the device not being operational. Most of the defects started with the poly2 layer. The first issue was depositing the poly2 layer with two runs at different temperatures. The first layer of poly was grown at 610°C for 1.1μm and 650°C for a final poly thickness of 2.6μm. This can affect the grain boundaries of the poly silicon interface and potentially affect the etch rate in the STS Deep Reactive Ion Etch (DRIE).

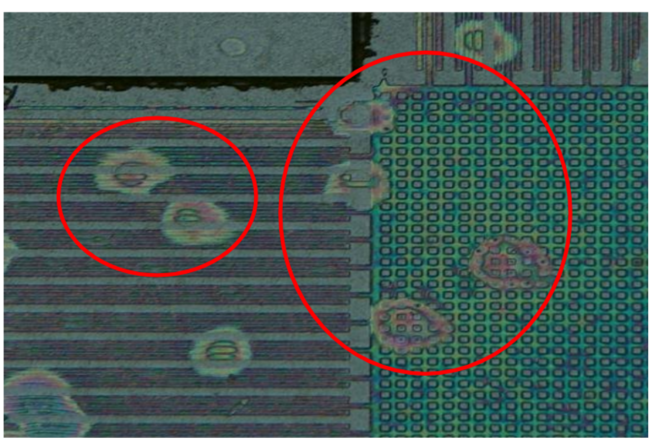

Figure 10: The Spin-on-Dopant particles across the device.

The doping process of this level left a lot of defects on the wafer due to the Spin-on-Dopant method. The SOD left particles across the entire wafer,which can be seen in the figure above, making the patterning of the poly2 very poor. There were issues with patterning the beams and fingers due to the change in refractive index of the light during exposure. The poly2 layer was designed to be doped with the Varian 350D Ion Implanter, but due to it being down, the SOD was the only alternative.

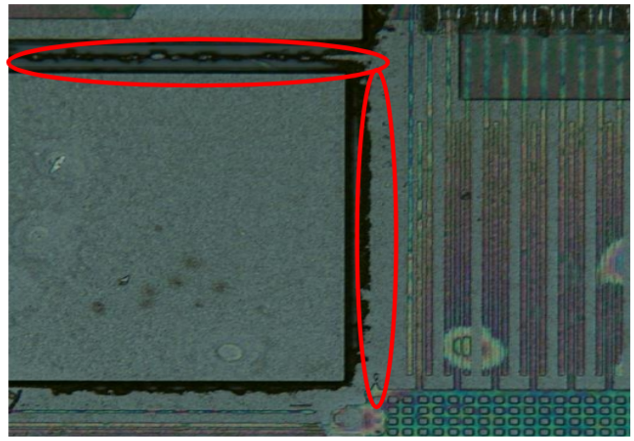

Figure 11: The spring beams were not patterned on to the poly2 layer, which is highlighted in red.

One of the critical defects of this fabrication process was the missing spring beams. Without this beam, there is no displacement of the device and support. The beams may have been designed to be 4μm, which may have been to small for the SMFL's capabilities. It did not survive the STS DRIE so future work must be done to optimize this process.

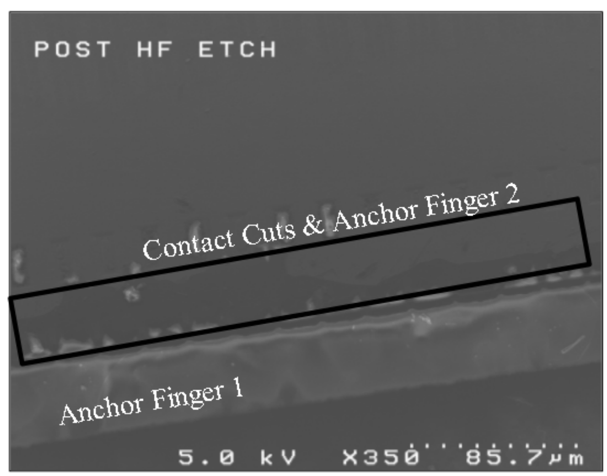

Figure 12: The photoresist was peeling during the BOE etch and there was removal of contact cuts.

The release of the fixed fingers, movable fingers, and proof-mass was a challenge with long etch times. The resist would peel if it was etched longer than 40 minutes. The resist was baked at only 110°C, which is not enough to sustain the etch. Future work can be performed to optimize the release process.

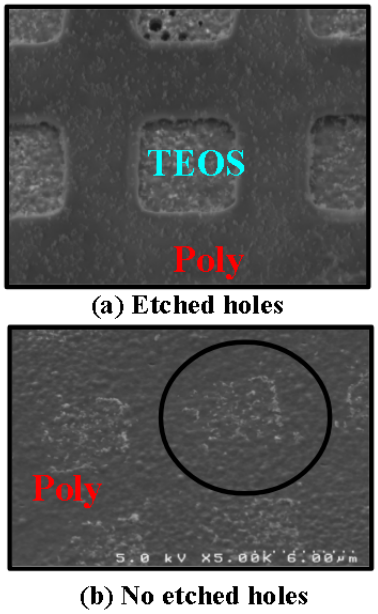

Figure 13: (a) The etch holes were completely etched down to the TEOS layer. (b) The etch holes were blocked by some remaining nitride/oxide layer and prevented release.

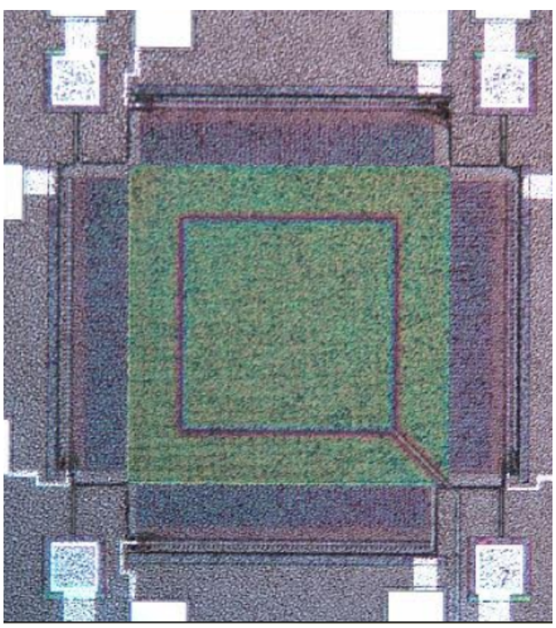

Figure 14: Fabricated Device.

Another issue with the release was that the etch holes through the proof mass were not etched during the STS DRIE process. This is most likely due to the oxide and nitride layers still on-top of the poly. Since the STS is highly selectively to Silicon/Poly, the oxide and nitride should be etched completely.

V. Conclusion

The design and fabrication of the surface MEMS three-axis accelerometer did not fabricate as well as expected. The fabrication process was done in the SMFL, with a 7 level process flow. The fabrication process had critical defects that affected the structure of the device. The issues with the second poly layer, SOD particles, missing spring beams, non-etched holes, and issue with release are processes that need to be improved before successfully fabrication the accelerometer.

A. Future Work

There are plenty of ways to improve on the fabrication process and minimize the defects. Future work on the deposition of the second poly layer will need to be characterized in simulations. ANSYS is not the optimal simulation software for MEMS devices. If there are some more specific software for MEMS design, that will help with the design of the poly structure on it's stress, strain, thermal stress, etc.

The poly2 should be ion-implanted, and not doped with SOD. Any risk of particle contaminants will be detrimental to the patterning of the poly.

To improve the spring beams and etch-hole processing, the patterning process should be characterized. The spring beams can be made thicker to account for over-etching. The nitride and oxide etch should be completely cleared out to allow etch-holes to be made. For the wet etch of the oxide, the wafers should be pulled out and put back in the BOE every 15 seconds to make sure the oxide is cleared out in between the finger gaps.

Future work for the release method can be to find the optimal hard bake temperature for the resist in the BOE 5:2:1. Another method can include different types of resists that may be more resistant to the BOE bath. A change in the release method can include a process with vapor HF, which has been seen in other papers [2] since wet etching may be too aggressive for the resist.

A project with one design can be processed with different types of sacrificial materials and then compared between the release methods. Materials such as Phosphosilicate Glass (PSG) can be used as the sacrificial layer because of it's higher etch-rate property in BOE.

VI. References

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Figure 15: Eddie Huang is from New York City, NY and is a 5th year undergraduate at Rochester Institute of Technology and in the Microelectronics Engineering BS program. He has co-oped at Global-Foundries in Malta, NY as a Yield Engineer Intern, and Product Engineering Intern in 2015 and 2016.