1. In this video [https://www.youtube.com/watch?v=32HXlchQgsw](https://www.youtube.com/watch?v=32HXlchQgsw) assuming that the SOI layer is 50um thick and the gaps are 2um,

1pt. for each part (2 pts. total)

a. Estimate the change in sense capacitance over the range of travel (shown 0:20 to 0:35)

1pt. for the approximately right value for $\Delta C_{total}$

The initial overlap for the capacitive sensor can be estimated to be about 70µm, as seen in the image below.

![Image 1](image1.png)

The final overlap distance with the capacitive sensor can be estimated to be about 532µm, as seen in the image below.

![Image 2](image2.png)

The initial capacitance is then:

$$C_i = N\varepsilon_0 \left( \frac{tx_i}{g} \right)$$
\[ C_i = 6 \times \left(8.85 \times 10^{-12} \frac{F}{m}\right) \times \left(\frac{(50 \times 10^{-6}m) \times (70 \times 10^{-6}m)}{(2 \times 10^{-6}m)}\right) \]

\[ C_i = 92 \times 10^{-15}F \]

\[ C_i = 92fF \]

The final capacitance is:

\[ C_f = N\varepsilon_0 \left(\frac{tx_f}{g}\right) \]

\[ C_f = 6 \times \left(8.85 \times 10^{-12} \frac{F}{m}\right) \times \left(\frac{(50 \times 10^{-6}m) \times (532 \times 10^{-6}m)}{(2 \times 10^{-6}m)}\right) \]

\[ C_f = 706 \times 10^{-15}F \]

\[ C_f = 706fF \]

The total change in sense capacitance is:

\[ \Delta C_{total} = C_f - C_i \]

\[ \Delta C_{total} = 614fF \]

\[ \Delta C_{total} = 0.614pF \]

b. Estimate the change in capacitance for one of the three poles, over a single step (0:44 to 0:57)

1pt. for the approximately right value for

One pole will have four sides, which should be multiplied to the total number of fingers, \(N_{fingers}\). This can be seen in the image below.

We can estimate the total number of fingers by first measuring the pole overlap distance of sides 1&2, as well as 3&4. Then, we measure that a finger is seen about every 12µm. Therefore, the total number of fingers is about 180. A close estimate is OK for this number since the total number was not strictly given and the images don’t allow a direct count of the number of fingers.
Therefore, (assuming the initial capacitance is zero when the fingers don’t overlap at all)

\[ \Delta C_{\text{total}} = N_{\text{fingers}} \varepsilon_0 \left( \frac{tx_{\text{overlap}}}{g} \right) \]

The overlap distance is equal to the width of the fingers, which was measured to be about 5µm.

\[ \Delta C_{\text{total}} = 0.4 \text{pF} \]

2. In the polyMUMP\(\bar{s}\) process, list the thin film layers that will be present on the substrate (starting at the substrate and working up, in order) before the release etch, in regions with the following masking layers

1 pt. for each correct part (5 pts. total)

a. POLY0, POLY1, POLY2, METAL
   Substrate, nitride, poly0, oxide1, poly1, oxide2, poly2, metal
b. ANCHOR1, POLY1, P1P2VIA, POLY2
   Substrate, nitride, poly1, poly2
c. POLY0, ANCHOR2, POLY2, METAL
   Substrate, nitride, poly0, poly2, metal
d. METAL
   Substrate, nitride, oxide1, oxide2, metal
e. DIMPLE
   Substrate, nitride, oxide1, oxide2

3. In the SOIMUMPs process, list the layers that will be present (starting at the handle wafer and working up, in order) at the end of the process, in regions with the following masking layers

1 pt. for each correct part (5 pts. total)
4. The layout below is to be made in the polyMUMPs process. Assume that the contacts are 2um square and
   a. draw a cross-section through AA of what the structure will look like before the final HF etch.

1 pt. for correct final cross section
1 pt. for the dimple under poly1
1 pt. for metal contacting poly2
1 pt. for having poly2 contact poly1 and poly0

5. Will both metal pieces remain on the wafer after the final HF etch? Why or why not?
   a. 2 pts. total: 1 pt. for correct answer, 1 pt. for explanation
Both metal pieces will not remain on the wafer after the final HF etch. This is because the leftmost metal layer was deposited over the Oxide2 layer. During release, Oxide2 will be etched away, taking the metal rectangle with it. The rightmost metal pad will remain on the wafer after the final HF etch because it is over the Poly2 layer, which will not be etched away.

6. The pictures below are of the ADXL202, which is now obsolete but looks a lot like the newer parts that replaced it. Die photo (CMOS+MEMS), SEM of the MEMS device, detail SEM, and simulation of response to a vertical acceleration.

9 pts. total

a. Using the scale bar, estimate the mass of the proof mass, assuming a 3μm thick polysilicon film.

1 pt. for an approximately right answer

Using the scale bar, and measuring around the mass, the central area is about 300x300μm² and each of the 4 corners is about 100x100μm². With a 3μm device layer:

\[ m = \rho V \]

\[ m = 2300 \left[ \frac{kg}{m^3} \right] \times \left( \left( 300 \mu m \right) \times \left( 300 \mu m \right) + 4 \times \left( 100 \mu m \right) \times \left( 100 \mu m \right) \right) \times \left( 3 \mu m \right) \]

\[ m = 0.9 \mu g \]

b. Using the sensor resonant frequency quoted on the datasheet, estimate the combined spring constant of all of the support springs.

1 pt. for an approximately right answer

From the datasheet, we see that the sensor resonant frequency is typically 10kHz, or 62.8k[rad/s]. Using the frequency equation to solve for the spring constant:

\[ \omega = \sqrt{\frac{k}{m}} \]

\[ k = \omega^2 \times m \]

\[ k = \left( 62.8 \times 10^3 \left[ \frac{rad}{s} \right] \right)^2 \times \left( 9 \times 10^{-10}[kg] \right) \]
\( k \approx 3.55 \left[ \frac{N}{m} \right] \)


c. In the detailed SEM, identify the proof mass, support springs, proof mass anchor, over-acceleration mechanical stops, differential sense capacitors (big), actuation capacitors (small).

1 pt. for each correct label (6 pts. total)

\begin{itemize}
  \item Proof Mass
  \item Overacceleration Stops
  \item Support Springs
  \item Differential Sense Capacitors
  \item Actuation Capacitors
  \item Proof Mass Anchor
\end{itemize}

d. Assuming a 3um thick film with 1um gaps, estimate the voltage needed across the actuator gap to support the weight of the proof mass (at 1 gravity).

1 pt. for an approximately right answer

The force equation for the output force of the actuation capacitors is:

\[ F = N \frac{1}{2} \varepsilon_0 V^2 \left( \frac{A}{g^2} \right) \]

Solving for the voltage, we obtain:

\[ V = \sqrt{\frac{2Fg^2}{N\varepsilon_0 A}} \]
At 1g, the force necessary to support the mass is 9nN. The overlap distance is measured to be about 40µm. The thickness $t$ is 3µm. Multiplying the thickness times the overlap distance, you obtain the overlap area $A$. The gap distance, $g$ is 1µm. Finally, the total number of actuation capacitors, $N$, is 16 in this case.

Solving for the voltage, we obtain:

$$V = 1[V]$$
7. [EE247A] In a three mask process (POLY0, C1S, POLY1) with only one structural polysilicon (POLY0 for wiring, and POLY1 for structures), design a 3 axis capacitive accelerometer. Can you do it with a single proof mass? Will the response be linear in all directions?

5 pts. for appropriate effort