NO CALCULATORS, CELL PHONES, or other electronics allowed. Show your work, and put final answers in the boxes provided. **Use proper units in all answers.**

1. [4] In the PolyMUMPS process, you draw a series of circles on layer POLY2. The smallest circle has a diameter of 20um, the largest is 120um, and the step size between circle diameters is 2um. A second array is identical to the first except there is a 2um diameter hole in the center of each circle (like a donut). You etch your chip for 1 minute in a solution that etches the oxide at a rate of 25.1 um/min. What is the smallest circle, and the smallest donut, still attached to the substrate?

$D_{circle}=$ **52um**   2 pts

$D_{donut}=$ **104um**   2 pts

2. [8] You have a made a force sensor with a strain gauge at the base of a beam. Three identical resistors make up the rest of a Wheatstone bridge. All resistors are nominally 10kΩ. The bridge excitation voltage is V_x=2V. The resistors all have a temperature coefficient $\alpha = 10^{-3}$/K, and a gauge factor G= -20.
    a. If the temperature goes down by 1 C, what is the change in resistance in a single resistor?

$$\Delta R = \alpha \Delta T R_o = (10^{-3}/K)(-1K)(10^4 \Omega)$$
$$= -10\Omega$$

$\Delta R=$ **−10Ω**   2 pts

    b. if the strain in the strain gauge increases +1 ppm (=10^{-6}), what is the change in resistance in that resistor?

$$\Delta R = G \varepsilon R_o = -20(10^{-6})(10^4 \Omega)$$
$$= -0.2\Omega$$

$\Delta R=$ **−0.2Ω**   2 pts

    c. If all resistors heat up by 10 C, what is the change in the bridge output voltage?

$V_{out}=$ **0V**   2 pts

    d. If the product of gauge factor and strain in the strain gauge is Gε=0.1%, what is the bridge output voltage?

$$V_{out} = \frac{V_x}{4} G\varepsilon = \frac{2V}{4}(0.001)$$
$$= 0.5 mV$$

$V_{out}=$ **0.5 mV**   2pts

3. [5] In the polyMUMPS process, if you draw three large concentric circles in your layout on layers DIMPLE, POLY1, POLY2 what is the list of materials in the center of the circle just before the HF release etch? Start at the silicon substrate and work up, in order.

substrate, nitride, Oxide 1, Poly1, oxide 2, poly2

1 pt for each correct thin film

4. [10] You have made a classic "Tang, Nguyen, Howe" comb drive resonator in a polysilicon process. You apply pure force $f(t)=F_0\sin(\omega t)$ and sweep the frequency over a wide range. You measure a low frequency deflection of 3um, and the maximum deflection of 90um occurs at 2,000 rad/s.

a. [4] What is the displacement at 20k rad/s? What phase? (write it as $A\sin(wt+\phi)$)

$x_{20k}(t)= 30_{nm}\ sin(20\kappa t - \pi)$

b. [4] What is the displacement at 20 rad/s? What phase?

$x_{20}(t)= 3_{\mu m}\ sin(20t)$

c. [2] You forgot to write down the phase at the maximum deflection. What would you guess it was?

90 -1

$\phi_{max}= -90\ or\ -\frac{\pi}{2}$

d. [2] What is the quality factor of the resonator?

$Q= 30$

5. [6] You have built a large parallel plate electrostatic actuator supported by a linear spring with spring constant K=1 N/m. The initial gap with no applied voltage is g_0=30um, and there is a gap stop that keeps the two plates from getting less than 2um apart (28 um of travel). You slowly increase the voltage, and at about 100 V the plate pulls in (becomes unstable and snaps down all the way to the gap stop).

a. [2] What is the displacement at pull-in (how much has it moved)?

$20_{\mu m}$ -1

$\delta x= 10\mu m$

b. [1] What is the spring force just before pull-in?

$F_{s,-}= 10\mu N$

c. [1] What is the spring force just after pull-in?

Same as 1b -1

$F_{s,+}= 28\mu N$

d. [2] After pull-in you decrease the voltage slowly. What is the approximate voltage at which the plate will pull-out? (you can have a square-root in your answer)

$\frac{100}{\sqrt{2}}$ -2 $\frac{100}{\sqrt{2.8}}$ -2

$V_{pull-out}= 10\sqrt{2.8}\ V$

6. [6] True or False (circle one)

T / (F) Usually in layout you draw where you want to keep both conductors and dielectrics

(T)/ F Electrostatic forces are scale-invariant (they remain the same as you change the scale)

T / (F) Pull-in voltage scales as the square root of S

(T)/ F If you triple the thickness of the polysilicon layer, the Q of a comb-drive resonator will increase by 3

T / (F) By varying beam width of a comb-drive resonator and measuring the resonant frequencies, you can estimate both E and ρ independently

(T)/ F Overetch of structural polysilicon will change both spring constants and the force of comb drives.