Probs 1-4	/24
5, 6	/24
7, 8, 9	/20
10	/10
11-14	/29
15, 16	/16
17	/8
18,19	/20
TOTAL	/151

EE147/247A Final, Fall 2020

NO internet allowed. Show your work, and put final answers in the boxes provided. Use proper units in all answers.

1. [4] A spring/mass accelerometer has a total capacitance of 10 pF with 1um line/space lithography, and a resonant frequency of 100k rad/s. Estimate the +/-1 g deflection, and the +/-1 g change in capacitance

2. [6] It is not uncommon for a MEMS comb drive with 2um gaps to be run at 200V.
   a. What is the average electric field in the gap

   b. How does it compare to the macroscopic breakdown field for air, 3 MV/m?

   c. How is this possible?

3. [8] In the polyMUMPs 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
   a. POLY0, METAL

   b. POLY1, P1P2VIA, POLY2

   c. POLY0, ANCHOR2, POLY2

   d. POLY1, METAL

4. [6] 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
   a. SOI

   b. TRENCH

   c. TRENCH, SOI, PAD METAL

5. [14] In an SOI process with a 10um thick device layer you have a very thin piezoresistive layer on the top surface. If you make a beam that is 100um wide and 1mm long, and apply a force perpendicular to the wafer surface

a. find the spring constant of the beam

b. find the strain at the surface of the beam as a function of force

c. find the strain at the surface of the beam as a function of deflection

You make a strain gauge at the base of the beam, and put it in a Wheatstone bridge with a 4V excitation voltage. The resistor has a gauge factor of +20, and a TCR of +0.1%/K. You have an instrumentation amplifier with a noise-limited resolution of 0.1μV.

d. Find the bridge output voltage as a function of strain

e. Find the minimum detectable force

f. Find the minimum detectable deflection

g. Find the temperature change that gives a noise-equivalent bridge output voltage

6. [10] A 100um long, 1um wide, 1um thick polysilicon beam has a Young's modulus of 150 GPa, the resistivity is 1 mΩcm, the TCR is 0.1%/K, the fracture strain is 1%, and the piezoresistive gauge factor is -20.

a. A transverse force of 1uN applied at the tip. What is the deflection and rotation of the tip?

b. An axial force of 1uN is applied to the beam above, what is the deflection of the tip?

c. What axial force is necessary to fracture the beam?

d. What is the electrical resistance from one end of the beam to the other?

e. If an axial strain of 0.1% is applied, what with the fractional change in the resistance be?

7. [6] In an SF6 plasma etching system with the wafer grounded,
   a. is the etching done primarily by chemical processes, or kinetic?

   b. Would you expect the etch to be isotropic, or anisotropic with vertical sidewalls?

   c. Would you expect the etch to have good selectivity between silicon and other materials?

8. [8] Describe the two phases of the Bosch Deep RIE process. What gases, what do they do, isotropic?, ions, etc.

9. [6] On a comb-drive resonator with a single mobile comb finger between two fixed comb fingers, you apply -150V on the moving structure, and 1.5V sin($1{,}000$ t) on the fixed input fingers. What are the frequency and magnitude of the resulting forces on the structure? The gap between the fingers is 2um, and the film thickness is 20 um. You may ignore fringing fields.

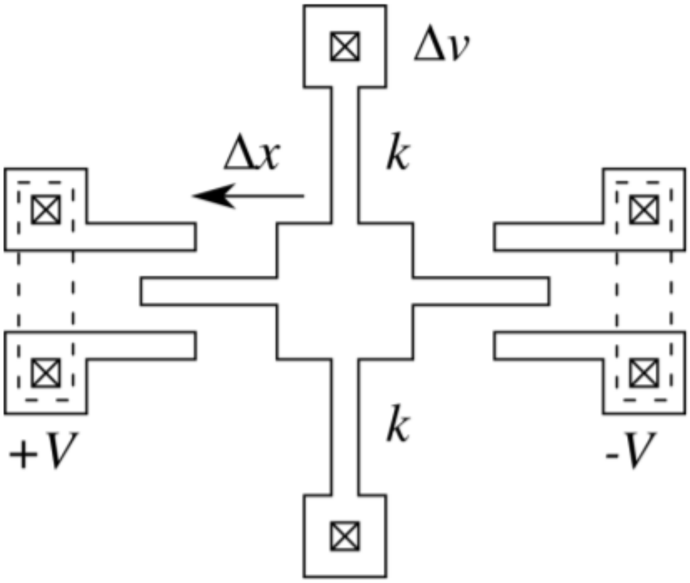
Frequency (radians/sec)	Magnitude

10. [10]

You know that the constant-voltage electrostatic force between two conductive parallel plates is $\frac{1}{2}\varepsilon V^2 A/g^2$. Using the fact that Q=CV and E=V/g,

a. write the force in terms of charge, not voltage
b. write the force in terms of electric field
c. write the force per unit area in terms of electric field

A differential comb-drive actuator is shown below. Fixed biases of $\pm V$ are applied to the fixed electrodes of the comb-drives, and a variable voltage, Δv, is applied to the movable electrode as shown in the figure:



a) Show that this scheme gives you a motion Δx that is linearly proportional to the applied voltage, Δv.
b) Assume a spring constant of 0.1N/m, a gap of 1 μm, and a thickness of 10 μm. What voltages do you need to move the electrode by 5 μm in the +x direction?
  - Note 1: assume |V|=|Δv|, in order to have the smallest voltages possible.
  - Note 2: when springs are in parallel, the spring constants are added to form an equivalent spring constant.
c) Would you also get similar linear displacement with a gap closing actuator?

11. [8] You have made a MEMS resonator with a spring constant of 1 N/m and a Q of 100. You apply a force with an amplitude of 1nN and various frequencies. What is the amplitude of the displacement when the force is applied:
    a. At $\omega << \omega_n$

    b. At $\omega = \omega_n$

    c. At $\omega = 2\ \omega_n$

    d. At $\omega = 10\ \omega_n$

12. [4] Write an equation using two definitions of the dot product to calculate the angle between the [111] and [100] crystal directions.

13. [9] Of the following process steps: spin casting photoresist, thermal oxidation, LPCVD polysilicon, which can be used with a wafer that has
    a. parylene on it; b. aluminum on it; c. silicon nitride on it

Existing film Process step	Parylene	Aluminum	Silicon nitride
Spin cast photoresist			
Thermal oxidation			
LPCVD polysilicon			

14. [6] Given two perfectly flat round plates of radius R separated by a nanometer-scale layer of water,
    a. what is the energy change associated with pulling the plates apart completely and exposing both sides to air (creating two new air/water interfaces)?

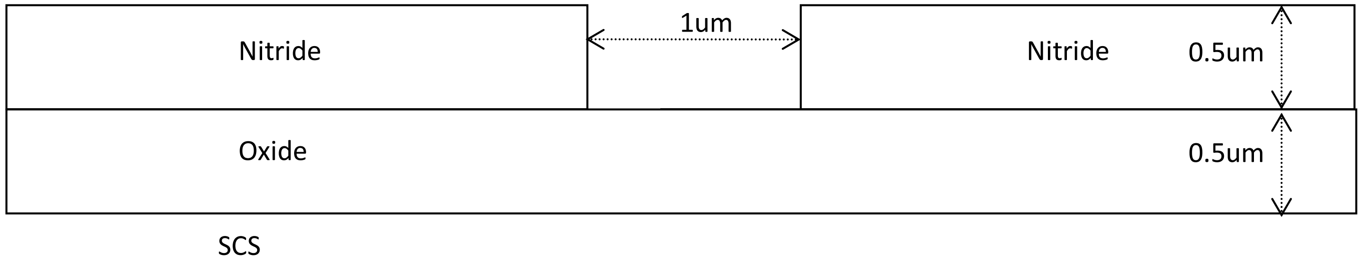
    b. If the distance that you need to pull the plates to separate them (and form the two air/water surfaces) is αR, where α is a small constant on the order of 0.001, what is the average force that must be exerted to separate the plates to that distance?

    c. Based on this model, what is the weight that can be supported by surface tension between plates that are 1mm in diameter?

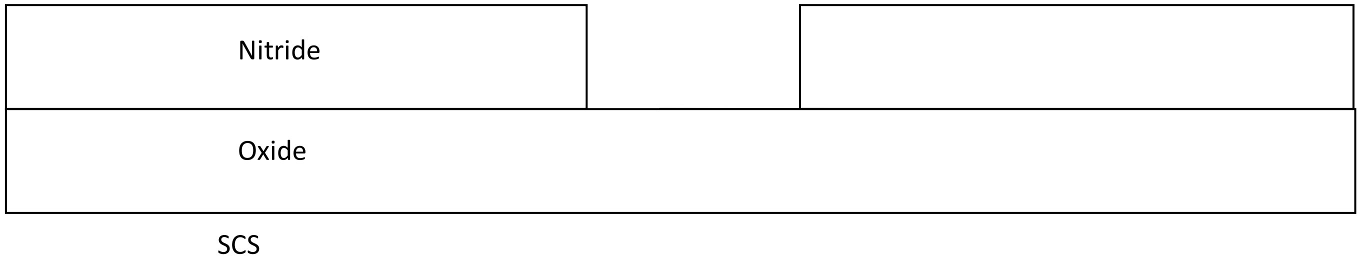
15. [4] Given two perfectly flat round plates of radius R with a micron-scale layer of water between them,
   a. Assuming a contact angle of 90 degrees, and considering only the air/water interface at the perimeter of the plates, what is the surface tension force pulling the plates together?

   b. If we ignore gravity and the surface tension force is balanced only by the Laplace pressure, what is the approximate radius of curvature of the resulting air/water interface? You may ignore the fact that the contact angle will change, and can assume that R >> 1 um.

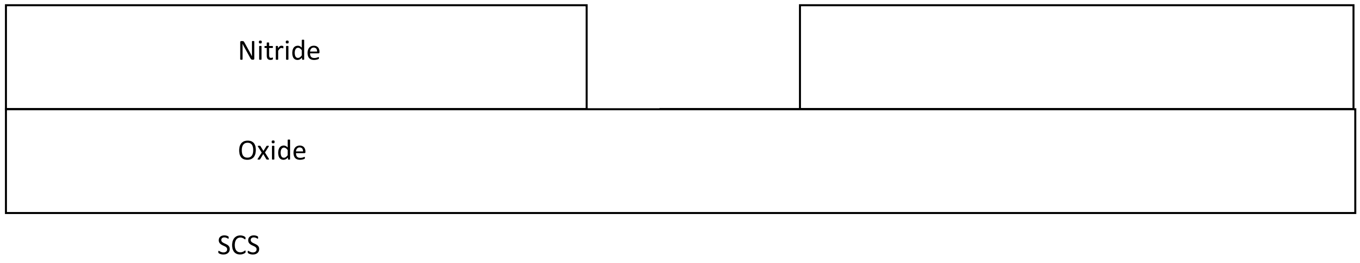
16. [12] You have a silicon wafer coated with a 0.5um thick thermal oxide, and a 0.5um thick silicon nitride layer. There is a 1 micron hole in the silicon nitride. Draw the cross-section after the wafer has been etched in the following ways. Draw on the figure provided. Each part below is a separate problem, not one etch after the other.
   a. Etched in an argon ion mill for an amount of time that will etch 0.3um of nitride



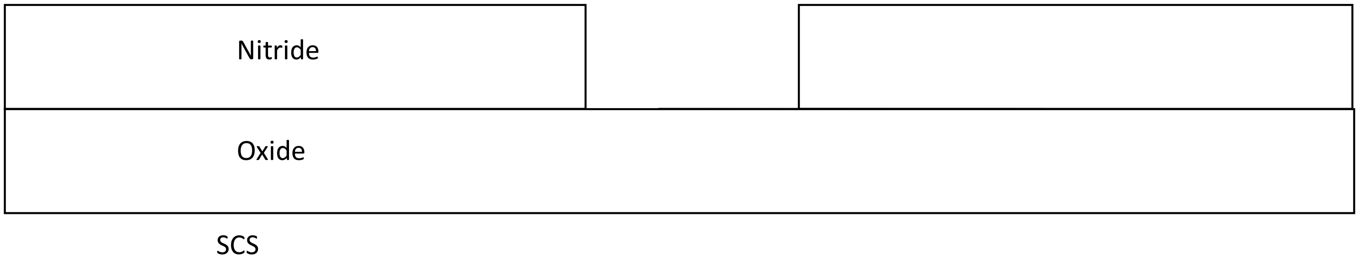
   b. Draw the same cross section, etched for 60 seconds in 49% HF (1 um/min etch rate) and then XeF2 for a 1 um silicon etch.



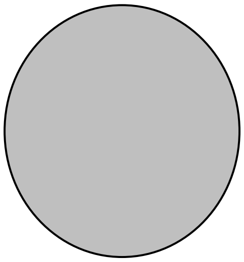
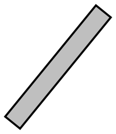
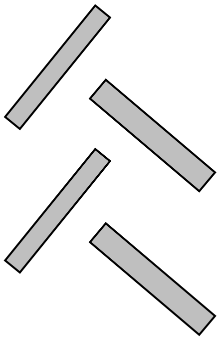
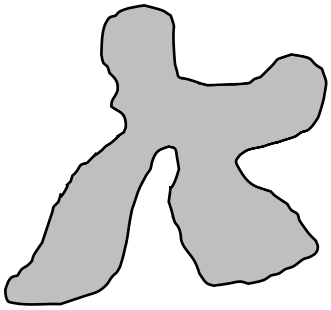
   c. Draw the same cross section, etched in an oxide RIE with a 100% overetch, 2:1 selectivity to silicon, and 10:1 selectivity to nitride.



d. Draw the same cross section, etched first in an oxide RIE with no overetch and infinite selectivity, followed by a 1um silicon RIE with 5:1 selectivity to nitride and oxide



17. [8] A (100) wafer coated with silicon nitride has the following regions opened to the silicon surface. The wafer is dropped in a KOH etch and the etch runs until only 111 planes are exposed. What is the outline of the etched regions under the silicon nitride (i.e. where is the region where the nitride will not be supported by silicon)? Assume that this page is oriented with the wafer flat.

18. [10] You have an accelerometer with $\omega_n=10^3$, K=1 N/m, and b=10^{-5} Ns/m at atmospheric pressure.
    a. What is the quality factor?

    b. Calculate the average thermal noise displacement of the spring.

    c. What is the power spectral density of the thermal noise due to damping?

    d. Calculate the average thermal noise force on the resonator, F_N, in a 1Hz bandwidth.

    e. What is the average displacement due to thermal noise in a 1Hz bandwidth at atmospheric pressure:
        i. near DC

        ii. at resonance

        iii. at 10 times the resonant frequency

19. [10] A piezoresistive acceleration sensor has a sensitivity of 10 mV per gravity. The piezoresistors have a combined effective impedance of 100 kΩ. Assuming no other noise sources,

    a. what is the voltage noise on the piezoresistors in a 1 Hz bandwidth at room temperature?

    b. What is the voltage noise on the piezoresistors in a 100 Hz bandwidth at room temperature?

    c. What is the noise-equivalent acceleration in a 100 Hz bandwidth at room temperature?

    d. If the temperature increases by 60 C to roughly 85C, what is the fractional change in the absolute temperature, and what is the resulting fractional change in the noise-equivalent acceleration?