Final
150 points

NAME:____

Instructions

Read all of the instructions and all of the questions before beginning the exam.

Unless otherwise noted on a particular problem, you must show your work in the space provided, on the back of the exam pages or in the extra pages provided at the back of the exam. Simply providing answers will only result in partial credit, even if the answers are correct. Draw a BOX or a CIRCLE around your answers to each problem.

Be sure to provide units where necessary.

GOOD LUCK!

PROBLEM	POINTS	MAX
1		20
2		20
3		50
4		60

Question 1 *Short answer questions* **(20 points)**

Governor Tarkin: *Evacuate? In our moment of triumph?*
I think you overestimate their chances.
- Star Wars

1. A polysilicon ***bridge*** is fabricated by depositing polysilicon over a sacrificial oxide layer on a silicon wafer, is doped and is then patterned and etched (both the polysilicon and the oxide are deposited only on *one side of the wafer*. The bridge is not released yet (that is the sacrificial oxide layer is not etched yet to release the bridge). Note that the bridge is anchored to the substrate at its two ends as is usually done in other examples we have seen in class. Assume that the thermal coefficient of expansion (TCE) of polysilicon is the same as that of the silicon substrate it is deposited on, and assume that the TCE of the sacrificial oxide layer is smaller than that of silicon and polysilicon. Assume that the deposition of both oxide and polysilicon is done using a LPCVD process, and that both layers are the same thickness. Answer the following questions. (circle all that apply):

   a. The bridge is not released yet. Choose the correct answer(s). After both oxide and polysilicon deposition, the wafer will (circle all that apply): **3 points**

      a) The wafer will remain flat
      b) The wafer will bow up and become like a cup
      c) The wafer will bow down, like a lens
      d) The wafer will expand out
      e) The wafer will shrink down

   b. The bridge is now released by etching the oxide away, answer the following question (circle all that apply): **3 points**

      a) The bridge will buckle up
      b) The bridge will buckle down
      c) The bridge will remain flat
      d) The wafer will remain flat
      e) The wafer will bow up and become like a cup
      f) The wafer will bow down

   c. The wafer, with the bridge on it, will now be cooled down by 100°C below room temperature. Answer the following question (circle all that apply):

      3 points

      a) The bridge will buckle up more
      b) The bridge will buckle up less
      c) The bridge will buckle down
      d) The bridge will expand out more
      e) The bridge will shrink down more

2. As discussed in class, in order to support mechanical structures we use several different beam designs, including a cantilever beam, a bridge structure, folded beams, and crab leg beams. The folded beam support is used because (for the following assume the same beam length, width, and thickness for all designs) (circle all that apply): **3 points**

    a) It is more flexible than a bridge structure occupying the same area
    b) It occupies less area than a bridge structure for the same spring constant
    c) It can accommodate a larger intrinsic stress than a bridge structure
    d) It is less prone to stiction than a bridge structure

3. The stable travel range (before pull-in) of a varying gap parallel-plate capacitive actuator can be increased by (circle all that apply): **4 points**

    - Increase the area of the capacitor plates
    - Increase the air gap distance
    - Increase the actuator thickness
    - Use a curved surface for one of the capacitor electrodes
    - Control the actuator with a voltage source
    - Control the actuator with a current source
    - Move the fixed drive electrode away from the middle of the capacitor

4. What are the sources of stress in a MEMS micromechanical structure (circle all that apply): **4 points**

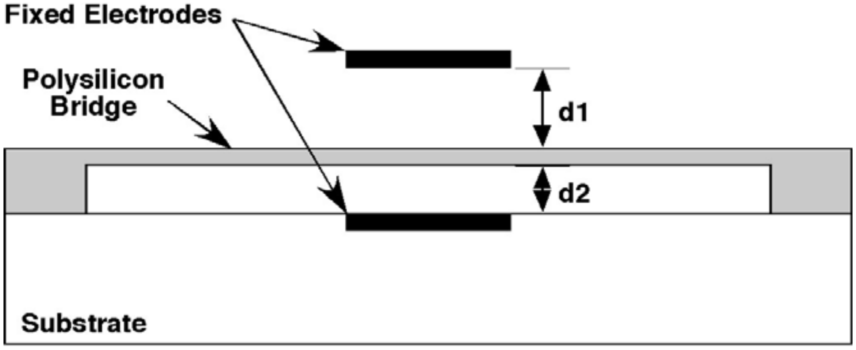
    Large thickness of the mechanical structure
    Deposition conditions of the deposited material, like temperature and gas flows
    Concentration of impurity dopants in the material
    Difference in thermal expansion coefficients
    Differences in the Young's moduli of the materials

Question 2 *Capacitive* (20 points)

Jake Blues: *I ran out of gas! I got a flat tire! I didn't have change for cab fare! I lost my tux at the cleaners! I locked my keys in the car! An old friend came in from out of town! Someone stole my car! There was an earthquake! A terrible flood! Locusts! IT WASN'T MY FAULT, I SWEAR TO GOD!*

- The Blues Brothers

This problem deals with a suspended bridge structure whose cross sectional view is shown below. It is anchored at its two ends. Two electrodes are placed above and below in the middle of the bridge, as shown. The air gaps between the bridge and the two electrodes are different, with d1 being larger than d2 as shown. The electrodes are stiff and cannot move. The bridge is L long and W wide, and has a thickness of h. A voltage V is applied between the bridge and each of the two electrodes (For example assume the bridge is at 0Volts, and each of the electrodes is at V Volts). Answer the following questions about this structure.



a) Upon the application of the voltage between the bridge and each of the two electrodes, the bridge will: **5 points**

- a) Move up
- b) Move down
- c) Remain flat

b) The voltage V is now steadily increased. Choose the correct answers: **5 points**

- a) The bridge will move down until it collapses
- b) The bridge will move down but will never collapse
- c) The bridge will move up until it collapses
- d) The bridge will move up but will never collapse

c) If we define the pull-in voltage as the voltage that the bridge will collapse, answer the following: **5 points**

- a) At the point of collapse, the bridge will have moved one third of the gap distance (of either d1 or d2 depending which electrode it is attracted to)
- b) At the point of collapse, the bridge will have moved less than one third of the gap distance of either d1 or d2
- c) At the point of collapse, the bridge will have moved more than one third of the gap distance of either d1 or d2

d) Compare the pull-in voltage of this double-electrode bridge with the standard single-electrode bridge:

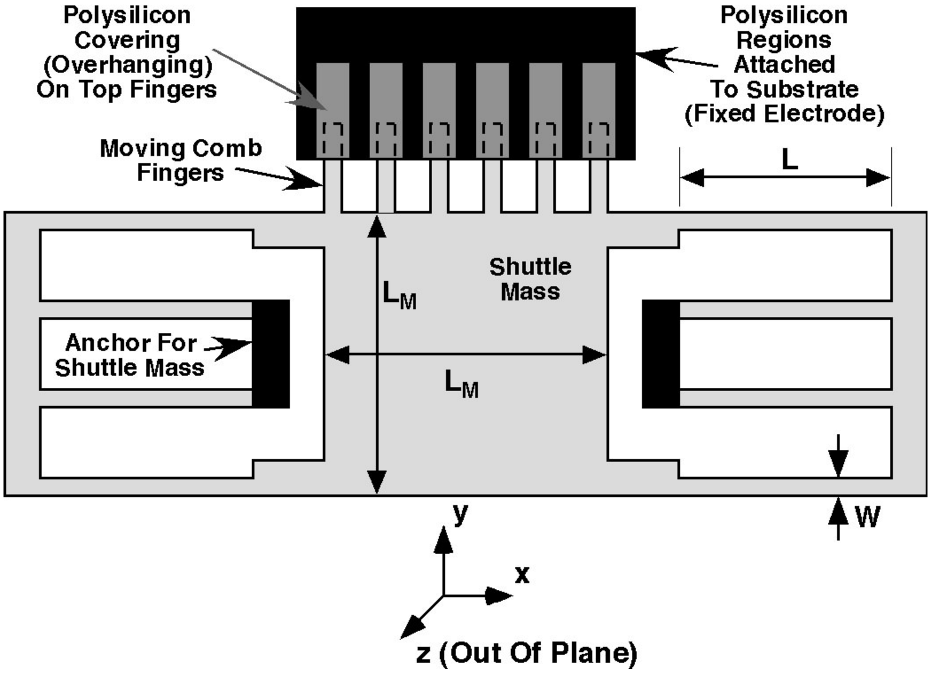
5 points

a) Double-electrode bridge has a higher pull-in voltage than single-electrode bridge
b) Double-electrode bridge has a lower pull-in voltage than single-electrode bridge
c) Double-electrode bridge has the same pull-in voltage as single-electrode bridge

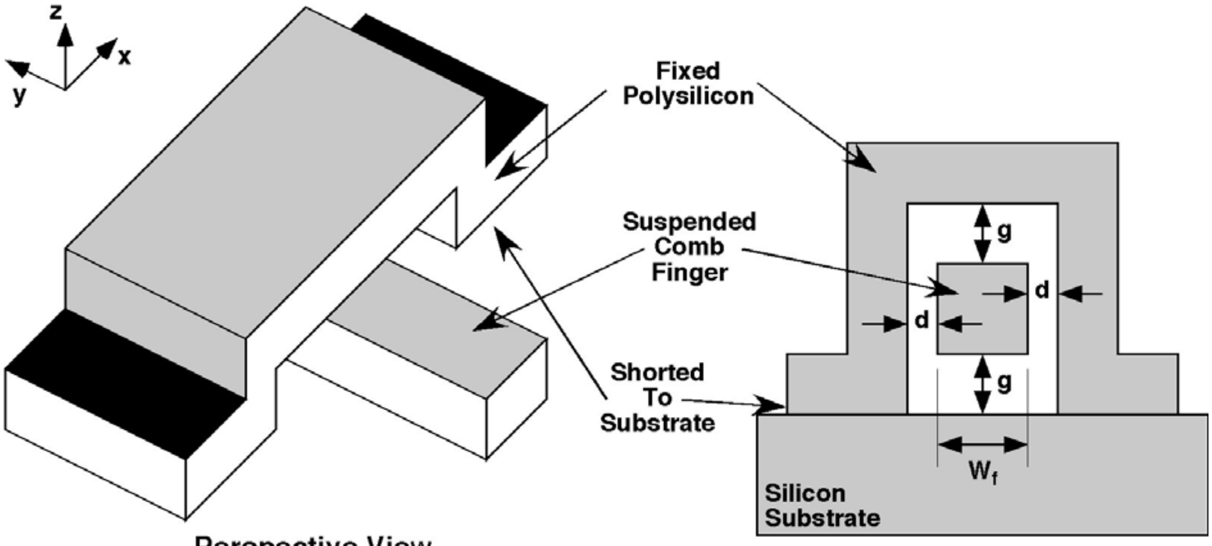
Question 3 *Capacitive II* **(50 points)**

Mallory: *I don't think I'm gonna make it. I feel so cold.*
-Natural Born Killers

This problem deals with the comb actuator structure shown below. The top view of the entire structure with folded beams is shown, as well as the perspective and side cross-sectional views of one of the comb fingers and one of the fixed electrodes. The rest of the problem description is provided on the next page.



Top View of the Comb Actuator



Perspective View
(The Si Subsrtate Underneath Is Not Shown)

Cross-Sectional View

Views of a Single Comb Finger

The polysilicon shuttle mass is suspended over the silicon substrate using a folded beam as shown. Note that both the polysilicon and the silicon substrate are electrically conductive. The fixed electrode wraps around the top of the moveable fixed fingers as shown. For the rest of this problem assume the following:

- The fixed electrodes and the silicon substrate are electrically ***shorted*** together.
- The shuttle mass with its comb fingers are electrically ***isolated*** from the substrate and the fixed electrodes through air gaps, and the anchor portion of the shuttle mass is electrically isolated from the silicon substrate.

Also, use the following dimensions and parameters for the rest of this problem:

- Young's Modulus for all Polysilicon = 170 Gpa
- All Polysilicon Thickness for Shuttle Mass and Comb Fingers = 6μm
- Comb Finger Width, W_f= 10μm
- You Do Not Need to Know Comb Finger Length
- Initial Gap Between Top of Comb Fingers and Bottom of Fixed Electrode, and Initial Gap Between Comb Fingers and Substrate g = 4μm
- Gap Between Side of Comb Fingers and Side of Fixed Electrode d = 2μm
- Initial Gap Between Shuttle Mass and Substrate = 4μm
- Folded Beam Arm Length L = 200μm
- Folded Beam Width W = 1 μm
- Shuttle Mass is Square with L_M = 440μm
- There Is a Total of 24 Comb Fingers On The Top Side of Shuttle Mass (Note Only Six Are shown)
- Note That There Are Two Folded Beams On Each Side of the Shuttle Mass
- Assume The Distance Between Tip of Comb Fingers and Back Surface of Fixed Electrodes Is Large.

a) **10 points**

Calculate the approximate spring constants in the y-direction (parallel to the wafer surface as shown), and z-direction (perpendicular to the wafer surface) for the shuttle mass. Note that the shuttle mass is supported by two folded beams, one on each side.

b) **10 points**

Now a voltage of 20V is applied between the moving shuttle mass and the fixed electrode on the top part of the figure. Note that since the fixed electrodes and the substrate are electrically shorted, there is also a voltage of 20V applied between the shuttle mass and the substrate. Calculate approximately how much the mass will move in the z-direction. Show your work and state any approximations you make.

c) **30 points**

With the same voltage of 20V applied as in Part b, calculate approximately how much the mass will move in the y-direction? Show your work and state any approximations.

Question 4 *Processing and Thermal* **(60 points)**

Ferris: *Incredible! One of the worst performances of my career*
and they never doubted it for a second.
-Ferris Bueller's Day Off

In this problem, you will be designing a structure and a process.

Your boss ask you to design a structure that consists of an undoped single crystal silicon island which is 300 um x 300 um x 20 um thick suspended at the end of a 1 um thick silicon nitride cantilevered membrane. A single gold line must run from outside the cantilever (i.e. the rest of the wafer) onto the membrane, connect to a polysilicon resistor on the silicon island and come back with a total resistance at 25 ºC of less than 10 kΩ.

a) How long would the cantilever have to be to ensure the island has a thermal time constant of 2 minutes? **(10 points)**

b) What doping level did you choose for your resistor and why? **(10 points)**

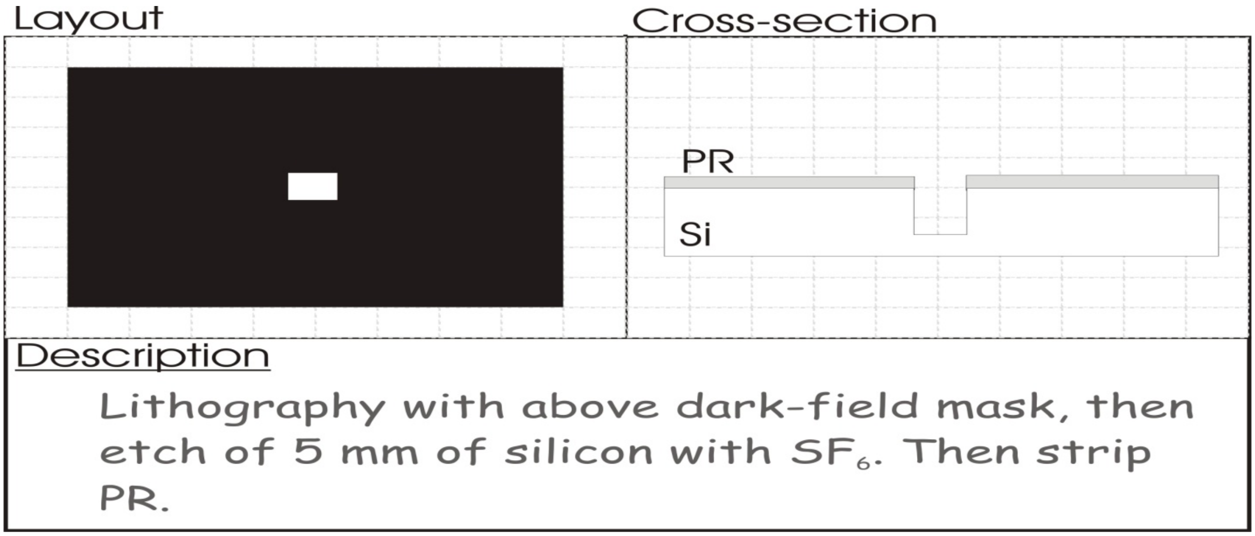
c) Given your design choice above, how much DC current would you have to provide to the resistor to heat the island to 500 K? **(10 points)**

d) Fill out a process sequence that will generate the device above. YOU MUST USE the process sheets in the subsequent pages. **(30 points)**

Each step has a space for:
1) that step's process description
2) a mask layout
3) space to draw a cross-section.

A sample is provided below (not related to the problem). YOU DO NOT HAVE TO PROVIDE ALL THREE COMPONENTS FOR EVERY STEP.

SAMPLE:



Lithography with above dark-field mask, then etch of 5 mm of silicon with SF_6. Then strip PR.

Layout

Cross-section

Description

Layout

Cross-section

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