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EE147/247A Final, Fall 2016

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. [17] True/False (circle one) 1pt each
   a. **True / False** SEMulator3D allows you to mesh and perform mechanical/electrical simulations on structures you design in layout (True/False)
   b. **True / False** A "LoadPatchNodes" boundary condition in CoventorWare is used to fix anchors during a simulation
   c. **True / False** The resistivity of silicon can be changed over many orders of magnitude just by adding less than 1% impurities.
   d. **True / False** In a silicon strain gauge, the fractional change in resistance ($\delta R/R$) is much greater than the fractional change in length ($\delta L/L$)
   e. **True / False** If you decrease all of the dimensions in an electrostatic actuator by 10 but keep the voltage the same, the force will go up by a factor of 100.
   f. **True / False** If you keep the dimensions of an electrostatic actuator the same, but increase the voltage by a factor of 10, the force will go up by a factor of 100.
   g. **True / False** If you change the sign of the voltage across a comb drive the force changes direction.
   h. **True / False** LPCVD polysilicon is conformal
   i. **True / False** LPCVD PSG is conformal
   j. **True / False** Evaporated aluminum is conformal
   k. **True / False** Sputtered aluminum is conformal
   l. **True / False** Plasma etching with SF6 is usually isotropic
   m. **True / False** Reactive ion etching with CF4 is usually isotropic
   n. **True / False** In RIE, sidewalls are protected by C4F8 cracked in the plasma.
   o. **True / False** In DRIE, vertical anisotropy is due to fluorine ions
   p. **True / False** You can use liftoff to pattern evaporated aluminum
   q. **True / False** You can use liftoff to pattern thermal oxide

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2. [24] Short answer, 2pts each. Give a brief description in support of your answer (a sentence fragment is fine).

a. When doing layout, if I draw a 10x10um2 rectangle on a layer called METAL1, would you expect to see a 10x10um2 square of metal on the wafer in that area, or a 10x10um2 hole?

b. When doing layout, if I draw a 10x10um2 rectangle on a layer called CONTACT that will be used to pattern an LTO, would you expect to see a 10x10um2 square of oxide on the wafer in that area, or a 10x10um2 hole?

c. Why would the capacitance be larger in a CoventorWare simulation than the simple parallel plate hand calculation? Fringing fields

d. If you wanted to accurately model the fabrication details of a new process you came up with, would you use SEMulator3D or CoventorWare? Why?

accurately models process

e. List three MEMS applications where more than one billion dollars in MEMS are sold each year.

XL, Gyroscopes, pressure sensors

-1 if not

f. The macroscopic breakdown field for air is roughly 3V/um. Why doesn't the air break down when we run 2um polysilicon gaps at 100V? (ideally give both a name and a short explanation)

Paschen, V 300 ... ← 3MV/m ... 7um d

1pt. name
1pt. explanation

g. Can we put 100V across 2um gaps with all materials (like metals)? Why or why not?

Not for metals

1 pts. for no +1 extra ?

1pt. explanation
1pt. right answer

h. Atoms have discrete energy levels. Crystals have bands of energies. Why?

Discrete atom energies form bands. Poly-exclusion → no two fermions in same system are allowed to have same energies.

i. Why do we anneal our wafers after ion implantation?

Drive in

j. During annealing after ion implantation, the surface concentration typically first goes up, then down. Why?

1pt. 1pt.

Initial surface conc. ~0, high conc. at range diffuses + brings up surface conc, but then surface conc. diffuses + levels out w/ rest of wafer

k. Give two reasons why we pump down to very low pressure in an aluminum evaporator.

Long mean free path → less contaminants → won't oxidize
better directionality →

1pt. each reason

l. How do we typically dope polysilicon for MEMS devices?

PSG

Dep. PSG
+1 Annealing Bet.. similar oxides
+1

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3. [4] Write an equation that would let you calculate the angle between the (110) plane and all planes in the {100} family in a silicon crystal. Solve it for all possible angles. (110) & $0\bar{1}0$ 010 => 45° +1, 001 => 90° +1, 100 => 45° +1, $\bar{1}00$

$a \cdot b = |a||b|\cos\theta$ +1

$1 = \sqrt{2}\cos\theta \rightarrow \theta = \cos^{-1}(\frac{1}{\sqrt{2}}) = 45°$

4. [3] List three isotropic silicon etches, one gas, one liquid, one plasma

Gas → XeF_2 ; Liquid → HNA, Plasma → SF_6

5. [3] List three anisotropic silicon etches, at least one liquid, at least one plasma

Liquid → KOH (TMAH?) ; Plasma → DRIE, RIE, sputter etch EDP

6. [4] You stretch (put a positive strain on) a piece of silicon, and the resistance goes down.

a. Can this happen with N-type silicon? How/why?

~~No (+) gauge factor~~ Yes with axial strain, negative G, increased mobility

b. Can this happen with P-type silicon? How/why?

Yes, (-) gauge Factor with transverse strain

7. [2] Your friend from Stanford deposited nitride, PSG, and polysilicon on a bare wafer, annealed it, and then dipped it in HF. She thinks that the HF must be dirty because the wafer looks awful. What do you tell her?

"poly" pox → annealing PSG and nitride → annealing PSG creates bubbling, cracks, gross

8. [2] After fixing her previous problem, with a new wafer she etches and releases a variety of long beams using a single-mask design. The beams all curl out of plane. What do you tell her?

~~Tensile stress on top of beams from nitride film~~

residual stress +1 Phosphorous from assymmetric PSG +1

9. [2] Your friend from MIT makes fun of your SOIMUMPS comb-drive calculations because you ignored the fringing field. He says that your calculations will be wrong by a factor of 2. What do you tell him?

The aspect ratio of SOIMUMPs (10:1) is high enough so the fringing fields will not matter.

10. [9] You have developed a new displacement sensor using a cantilever with a piezoresistor in a Wheatstone bridge. The bridge resistance is 1kΩ. The stiffness of the cantilever is 40 N/m. The damping coefficient is 0.025Ns/m at atmospheric pressure, which gives a very low Q, close to 1.

a. What is the average displacement noise of the cantilever over all frequencies? (formula and number)

$\frac{1}{2}kx^2 = \frac{1}{2}k_BT$ $x = \sqrt{\frac{\frac{1}{2}k_BT}{\frac{1}{2}k}} = \sqrt{\frac{2\times10^{-21}J}{1/2(40N/m)}} \approx \sqrt{\frac{10^{-21}}{10}} = \sqrt{10^{-22}}\ (10^{-22})^{1/2} = 10^{-11}$? 2

b. What is the power spectral density of the noise force on the cantilever? (formula and number)

$F_n = \sqrt{4k_BT\,b\,\Delta f}$ $= \sqrt{4\times10^{-21}\times\frac{1}{40}\Delta f} = \sqrt{\frac{4\times10^{-21}}{10}\Delta f} = 2\times10^{-11}\sqrt{\Delta f}$ 2

c. What is the displacement noise in a 100 Hz bandwidth at low frequency? (formula and number)

$x_n = \frac{F_n}{k} = \frac{1}{2}\times10^{-11}$ 2

d. If the damping decreases by four orders of magnitude at low pressure, 10^4

i. how does the average noise displacement of the cantilever change? (e.g. increase 2x, decrease 10%, etc.)

Does not change 1

ii. how does the power spectral density of the noise force change?

Decrease → x100 1

iii. how does the displacement noise in a 100 Hz bandwidth at low frequency change?

Decrease x100 1

/11

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11. [4] 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 $\omega << \omega_n$

$$x_{LF} = \frac{F}{k} = \frac{1nN}{1 N/m} = 1nm$$

b. At $\omega = \omega_n$

$$x_{\omega_n} = Q\,x_{LF} = 100nm$$

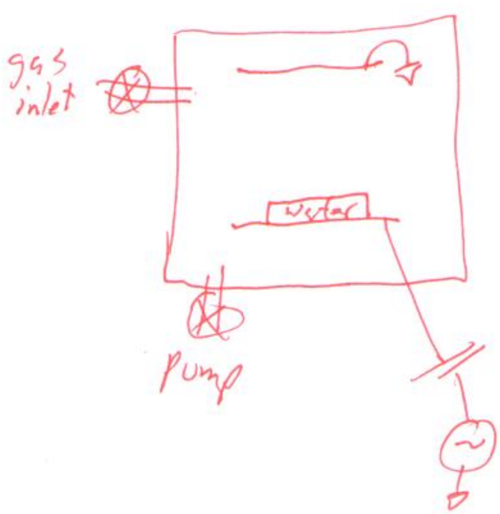
c. At $\omega = 2\,\omega_n$

$$x_{2\omega_n} = \frac{1}{3}x_{LF} = \frac{1}{3}nm \qquad \frac{1}{4}nm \text{ OK}$$

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

$$x_{10\omega_n} = \left(\frac{\omega_n}{10\omega_n}\right)^2 x_{LF} = \frac{1}{100}x_{LF} = 0.01 nm$$

12. [8] Sketch a CF_4 polysilicon reactive ion etcher, showing gas inlet, pump, power supply wiring, wafer, and ground. Describe two etching mechanisms and one deposition mechanism that happen during etching (chemical, kinetic, PECVD, ions, who, what, where, etc).

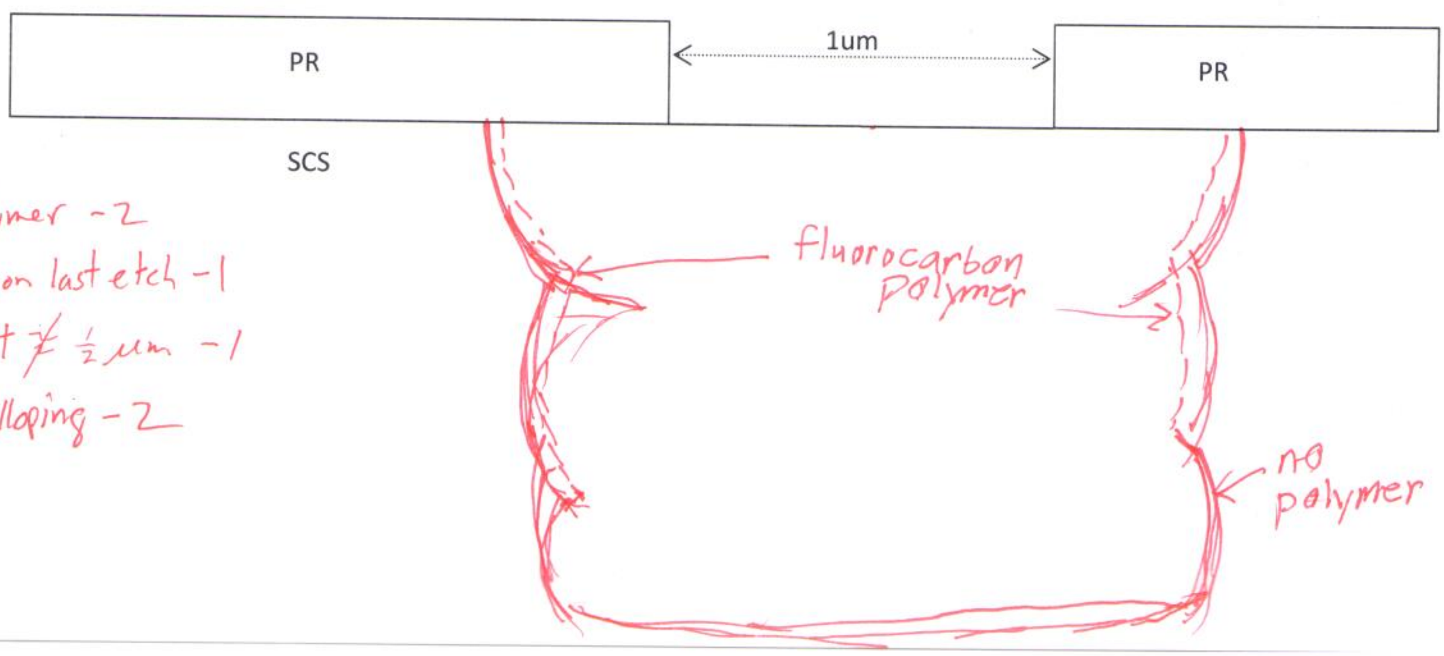


5 pts for figure
missing cap -1

1pt each for
F or halogen chemical etching
ions sputter CF_x polymer
CF_x forms on sidewalls

13. [5] You have a silicon wafer coated with photoresist. There is a 1 micron hole in the photoresist. Draw the cross-section after the wafer has been exposed to two and a half cycles in a DRIE etcher (etch, dep; etch, dep; etch). Assume 0.5um per etch step. Label any materials other than silicon and photoresist.

no polymer -2
polymer on last etch -1
undercut ≠ ½ um -1
no scalloping -2



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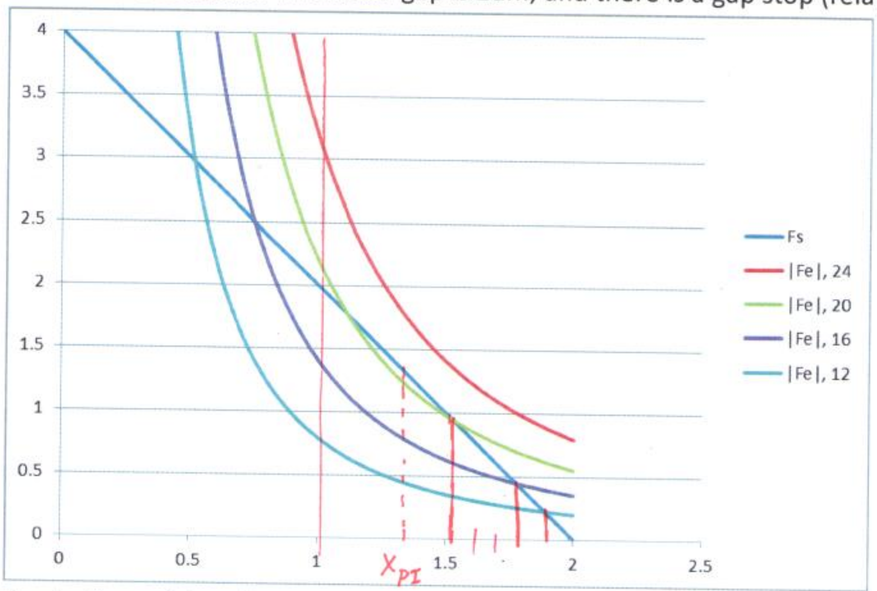
14. [8] The figure below shows the spring force and the magnitude of the electrostatic force for a gap-closing relay actuator running at four different applied voltages: 12, 16, 20, and 24 volts. The horizontal axis is in microns, the vertical in micronewtons. The initial gap is 2um, and there is a gap stop (relay contacts) at 1um.



V	g
12	1.9
16	1.8
20	1.5

a. Estimate the pull-in voltage

>20V ≈21V <24V

b. Estimate the pull-out voltage

<20V ≈19 >16V

c. Estimate the force on the relay contacts if 24V is applied

$F_e - F_s = 3\mu N - 2\mu N = 1\mu N$

d. Carefully sketch the displacement of the actuator as the voltage is increased from 0 to 24V, and then decreased from 24 to 0. Try to use specific points from the graph above. No sloppy sketches!

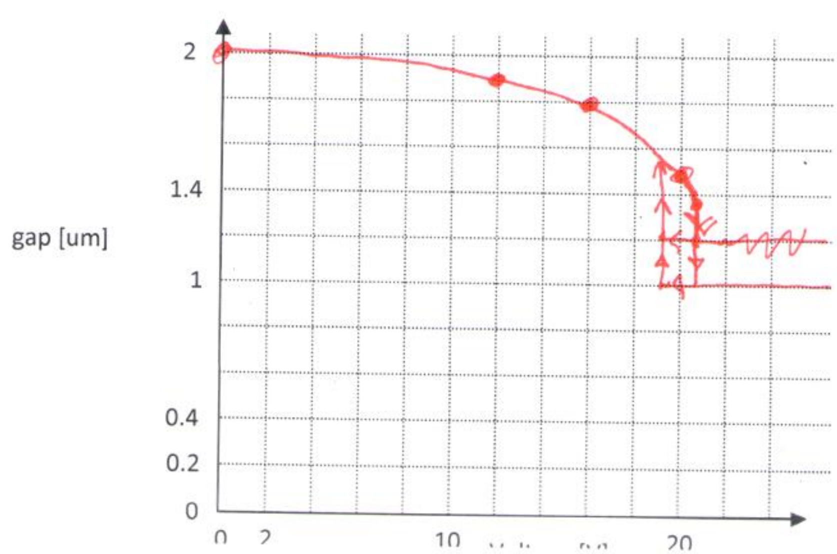
+1 Stops at 1 um

+2 has pts from data figure

+2 consistent w/ a, b

4 points from graph above, plus $g_{PI} = 1.33$

not vertical -1



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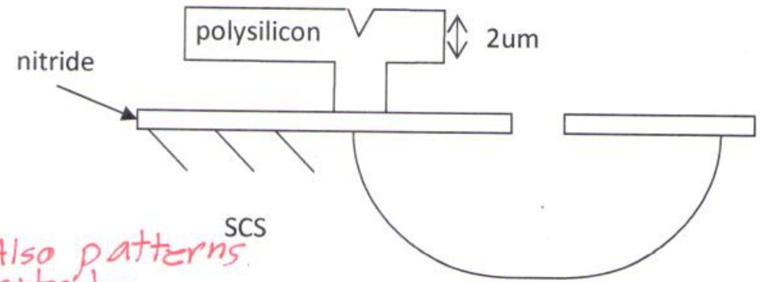
14. [6] Write down a process flow that would let me make the following cross-section.



LPCVD Nitride

LPCVD Oxide / ANCHOR

LPCVD Poly / POLY

LPCVD Oxide / HOLE ← Also patterns nitride

XeF_2 Etch

HF release

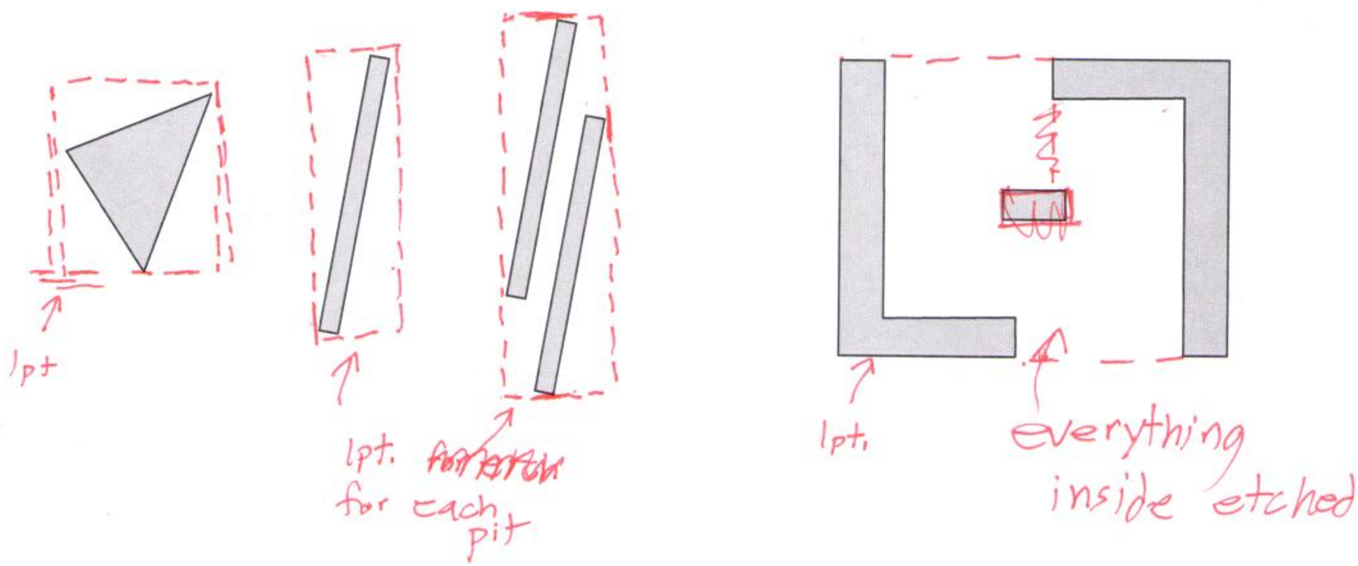
~~pts for layers + Mask names~~

2 pts for for poly before substrate etch

2 pts for protecting poly

2 pts HF release at end

15. [4] A (100) wafer coated with silicon dioxide 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 dioxide (i.e. where is the region where the SiO2 will not be supported by silicon)? Assume that this page is oriented with the wafer flat.



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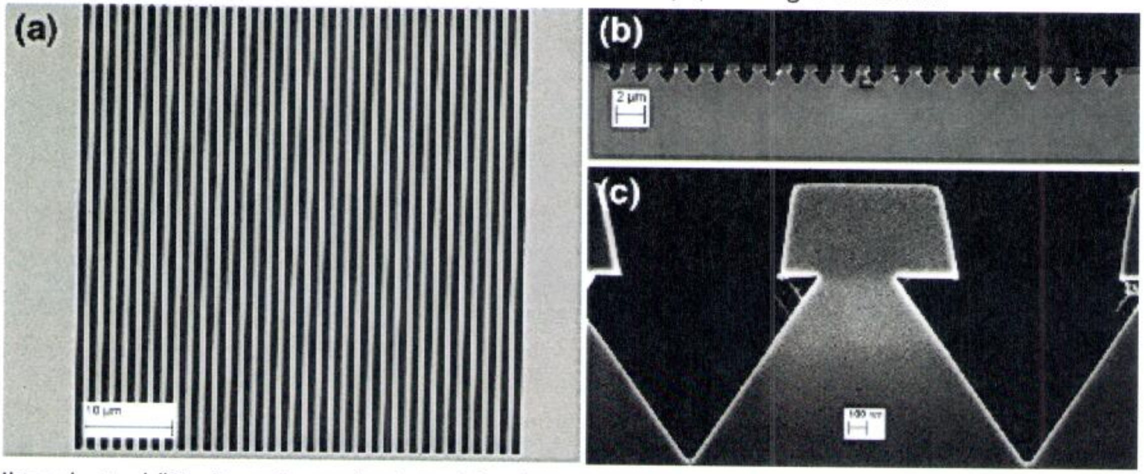
16. [6] The structure below has a layer of silicon nitride on (100) single-crystal silicon. On the left is a top view, on the right is a cross-section. The scale bar on the left is 10um, on the right is 100nm.



Kemiktarak et. al "Cavity optomechanics with sub-wavelength grating mirrors", NJP V14, Dec 2012

a) Write down a simple process flow that would create this device

LPCVD Nitride /PIT
KOH Etch

+2 for nitride
+2 KOH etch
~~+1 for nitride~~

b) Are the features on the left perfectly aligned with the <110> directions? How do you know?

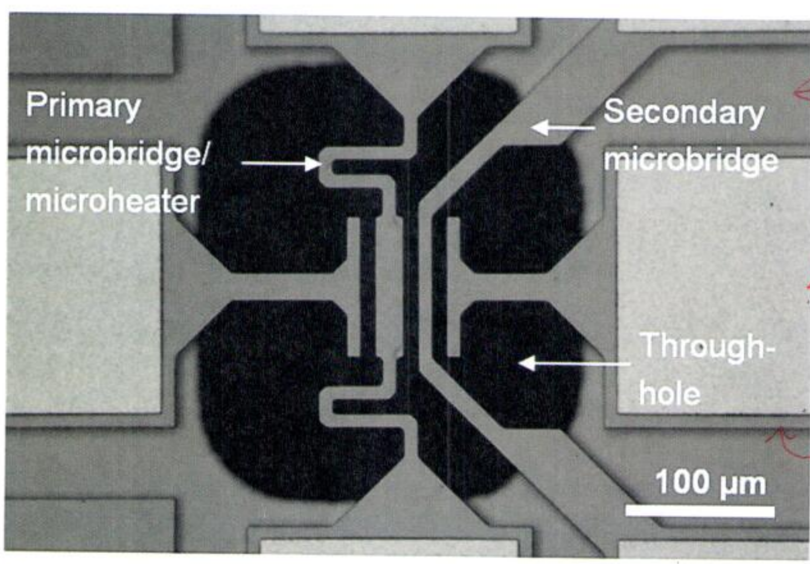
No, offset of undercut in (c) +2

17. [4] The structure below is made in a standard process.

a. What is the process?

SOIMUMPS +1

b. What are the names and materials of the three different layers that are visible? Draw an arrow identifying each one in the figure.



← Substrate
← Metal
SCS Dev. layer

+1 for each layer

Haugen, et al. "Integration of Carbon Nanotubes in Microsystems: Local Growth and Electrical Properties of Contacts", Materials 2013, V6N8.

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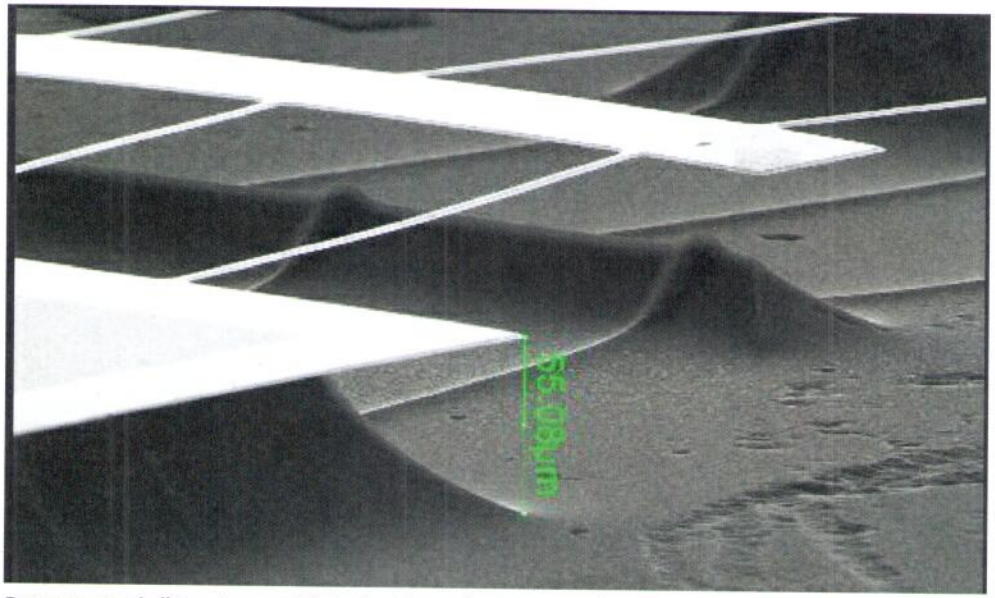
18. [3] The structure below is made from aluminum. The only other material is silicon. Write down a process that could create this structure.



- 1um Al evap. 1
- isotropic etch Al 2
- isotropic SF_6 Si etch 3

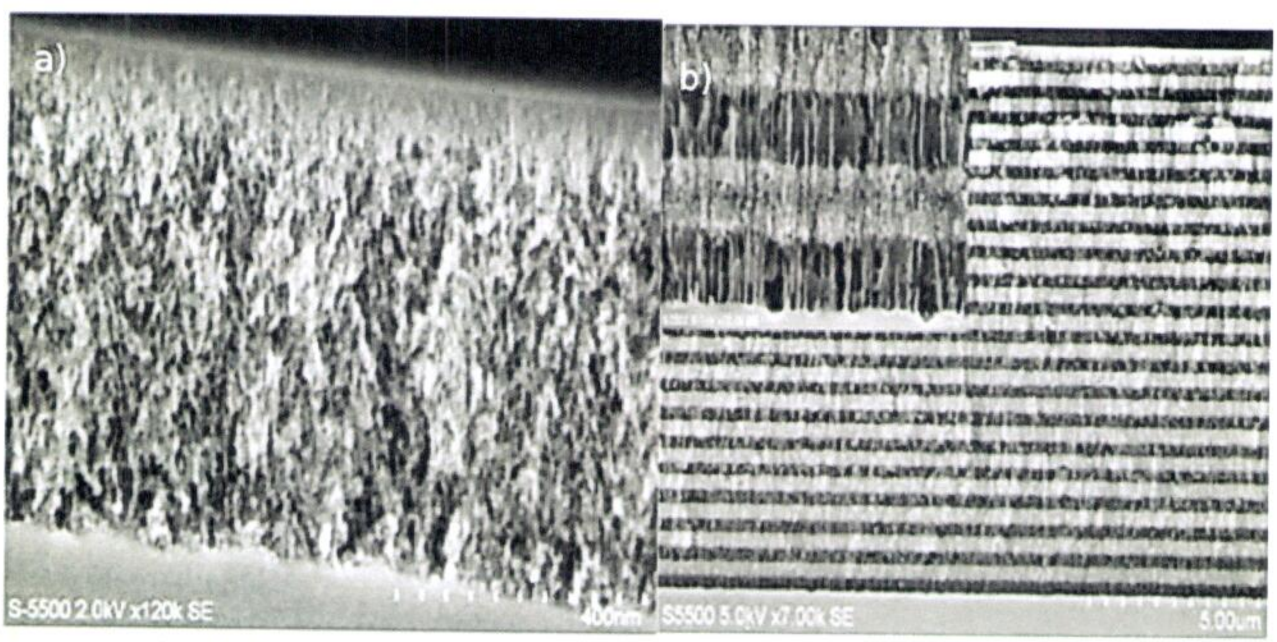
XeF_2
plasma

Baracu et al.,"Design and fabrication of a MEMS chevron-type thermal actuator", NANOTEXNOLOGY 2014.

Total
136

19. [4] The figure below is a cross-section of structures that are all silicon.
   a. What process would produce this?
   Electrochemical etching of porous Si 2 pts.

   b. How would the horizontal stripes be created? *
   Vary pore size by varying current density 2pts.



M. B. de la Mora, M. Ocampo, R. Doti, J. E. Lugo and J. Faubert, Chapter 6, "State of the Art in Biosensors - General Aspects"

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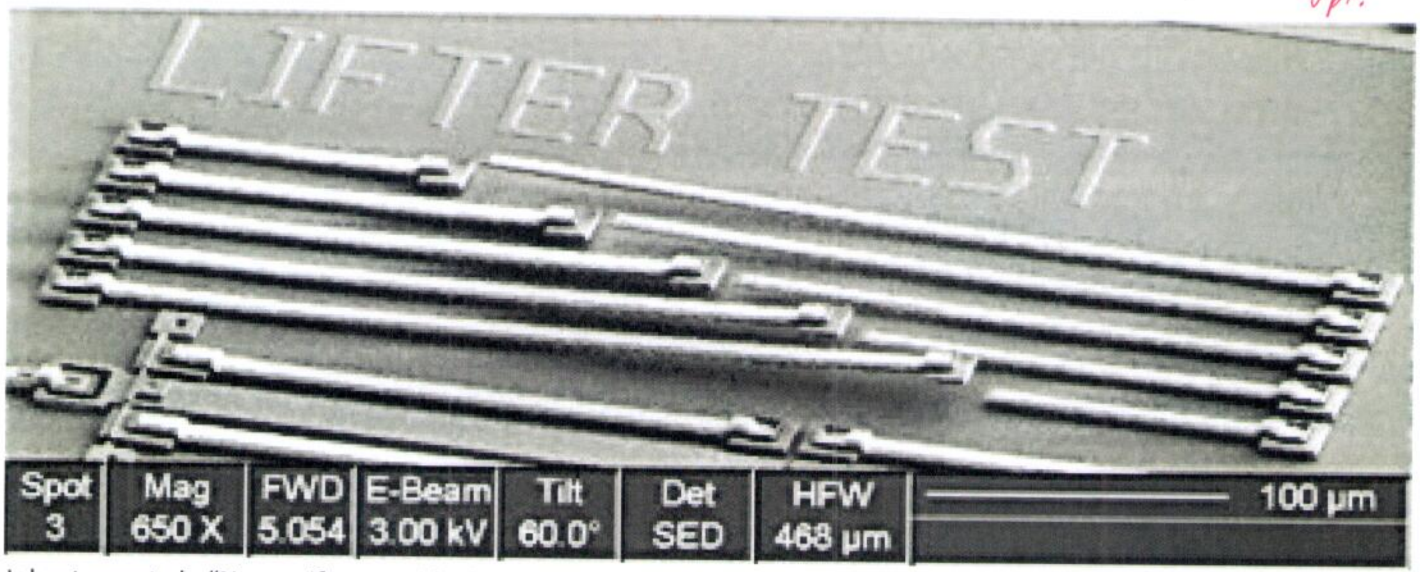
20. [10] The upper left structures in the figure below were made in polyMUMPs, and consist of METAL on POLY2, with POLY1 squares on both ends, one anchored, one free.

a. Is the stress in the metal tensile or compressive? Why?

Tensile -> curved up, metal wanted to "squeeze inward"? 2pt.

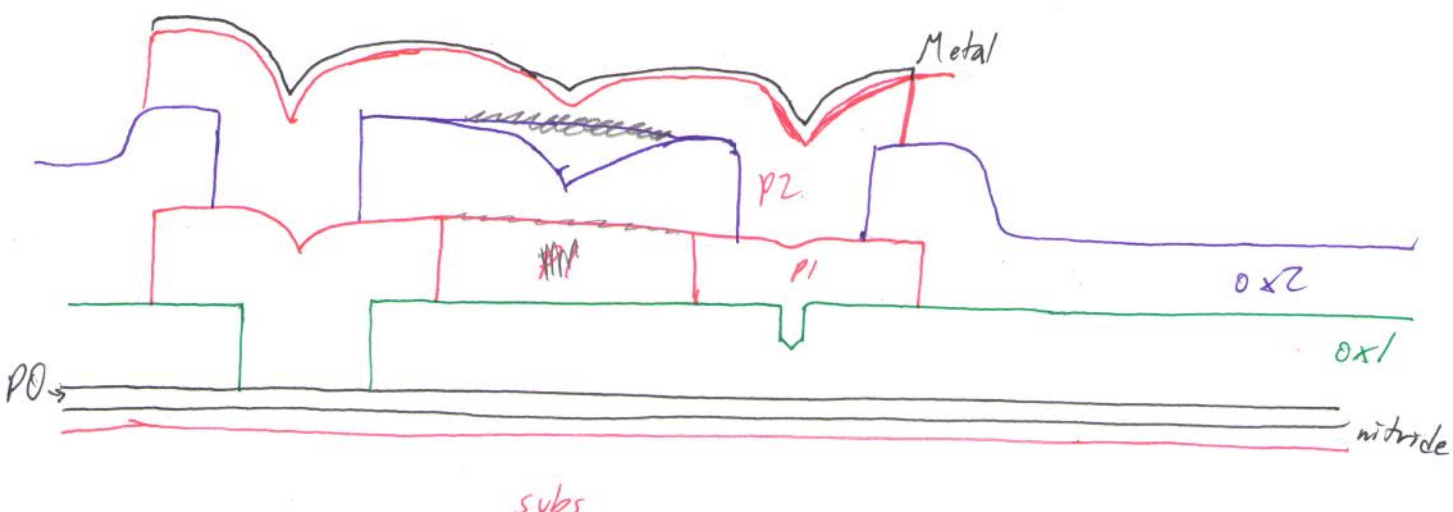
b. Sketch the layout of the shortest structure (upper left), and draw a cross-section (before HF release) beneath your layout.

8pt.



Johnstone et al., "Non-uniform residual stresses for parallel assembly of out-of-plane [...]", JMM 2006.

[4]



[4]

Al->
P1
P1P2VIA ----
together {P2 & Metal

P1
P1P2VIA
Al

P2+MET

P1
P1P2VIA

1pt. per layer?