Name KEY

SID

Page 1	/26
2	/26
3	/20
4	/28
5	/20
6	/24
7	/24
8	/12
TOTAL	/180

EE147/247A Final, Fall 2014

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. [26] True/False (circle one) 2pts each
   a. True / [✓ False] The only commercially available MEMS products are pressure sensors, accelerometers, and gyroscopes.
   b. [✓ True] / False MEMS are low cost in part because the fabrication techniques leverage integrated circuit fabrication processes and equipment.
   c. True / [✓ False] Silicon dioxide is stiffer than silicon.
   d. [✓ True] / False Silicon has a higher thermal conductivity than silicon dioxide.
   e. [✓ True] / False Poisson's ratio for incompressible materials is 0.5
   f. [✓ True] / False Residual stress gradients in polysilicon are typically caused by dopant atoms.
   g. [✓ True] / False The compressive stress in silicon dioxide is typically caused by dopant atoms.
   h. True / [✓ False] The maximum voltage across a MEMS electrostatic actuator at atmospheric pressure is typically limited by field emission.
   i. True / [✓ False] If you apply a voltage V to a gap-closing actuator, the moving plate pulls in. If you apply a voltage –V, the moving plate pushes out.
   j. True / [✓ False] Mechanical damping of MEMS devices operating in air is primarily due to heating of the structural material and anchors.
   k. [✓ True] / False You can fit dozens of transistors in an area smaller than the cross-section of a minimum-sized polyMUMPS beam.
   l. True / [✓ False] In an RIE etcher, the wafer is placed on the grounded electrode.
   m. True / [✓ False] In a plasma etcher, the etching is primarily due to kinetic processes.
   n. True / [✓ False] In a sputtering system, atoms on the target are dislodged by reactive gases.
   o. [✓ True] / False In a DRIE system, very small openings tend to etch slower than larger ones.
   p. True / [✓ False] Breathing phosphine is good for your health.
   q. True / [✓ False] The growth rate of a wet thermal oxide is constant over a period of 10 hours.
   r. True / [✓ False] Semiconductors are just like metals, but with fewer electrons.
   s. [✓ True] / False Semiconductors are just like insulators, but with smaller band gaps.
   t. True / [✓ False] A silicon structure coated with OTS or DDMS is hydrophilic.
   u. [✓ True] / False During drying, longer beams stick more than shorter beams.
   v. True / [✓ False] With a piezoresistive sensor there is no lower limit to the strain that you can detect if you build a big enough amplifier.
   w. True / [✓ False] You can deposit polysilicon by LPCVD on top of aluminum.
   x. [✓ True] / False You can deposit aluminum by evaporation on top of polysilicon.
   y. [✓ True] / False You can deposit SiO2 by LPCVD at 450C on top of silicon nitride.
   z. True / [✓ False] You can mask the growth of a thermal oxide on silicon with photoresist

Name______________________ SID______________________

2. [26] Short answer. Give a brief description in support of your answer (a sentence fragment is fine).
   a. Other than spin-casting, give one example of another way that photoresist is applied to a wafer, and explain why this method might be used instead of spin-casting.

      air brush, spray, adhesive film
      covers large features, avoids air bubbles

   b. Why are etch holes used in MEMS plates?

      faster release of large structures

   c. Why are dimples used on MEMS structures?

      minimize stiction/adhesion

   d. What is the layout convention for drawing conductors and dielectics? Do I draw what I want to keep, or what? draw conductors and holes in dielectrics

   e. Of the standard processes (polyMUMPS, SOIMUMPS, CMOS+post-processing/Fedder, Invensense/Nasiri) that we talked about this semester, which would you use to make
      i. an accelerometer with amplifier and analog to digital converter

         either Fedder or Nasiri, amplifier requires CMOS

      ii. a large force electrostatic inch-worm motor

         SOIMUMPS - higher aspect ratio means more force

      iii. a rotary electrostatic motor

         polyMUMPS - only one w/ 2 layers needed to make a rotor

      iv. a micro Christmas Tree, with wiring inside the structure to individual polysilicon heaters

         CMOS/Fedder - only one w/ wires inside the structure

   f. The Euler/Bernoulli beam model that we developed and used all semester is a good approximation for most MEMS applications. When does it not work well?

      when dy/dx is not $\ll 1$

   g. To maximize response to a transverse force, should a piezoresistive sensor layer be placed
      i. at the center of a beam, or on the surface?

         surface - strain increases linearly w/ distance from neutral axis

      ii. at the base of the beam, or at the tip?

         base - strain increases linearly w/ distance from applied force

   h. In a piezoresistive Wheatstone bridge, if the chip heats up the output of the bridge will change. Why, and how much (a lot, a little, ...)?

      TCR of resisters. Change is small in a balanced bridge

   i. If the thermal noise power spectral density is constant over all frequency, why does most of the thermal noise in a MEMS resonator usually show up at the resonant frequency?

displacement response to force is greatest there

3. [5] Write an equation that would let you calculate the angle between the (110) plane and the (111) plane in a silicon crystal (you don't need to solve the inverse trig problem, but simplify the easy parts)

$|x||y|\cos\theta = x \cdot y$ +3 $\cos\theta = \frac{2}{\sqrt{6}}$ +2 simplifying

$x = \langle 1,1,0 \rangle$ $x \cdot y = 1\cdot1 + 1\cdot1 + 1\cdot0 = 2$

$y = \langle 1,1,1 \rangle$ $|x| = \sqrt{2}$ $|y| = \sqrt{3}$

4. [15 total] Given the following process flow and masks, draw the cross section **before the PLY2 etch, showing PLY2 photoresist**. The C2x contacts are 2um square. I've given you a few lines to make drawing easier. They may or may not have anything to do with your layers. Assume infinite selectivity. **Label materials.**

2um LPCVD PSG

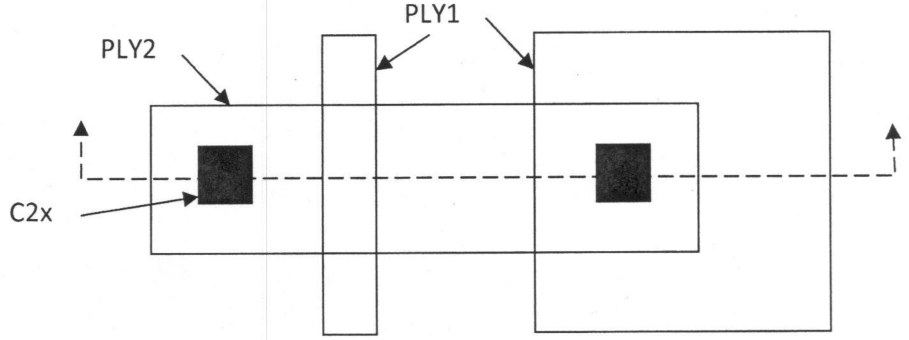
2um LPCVD poly / PLY1

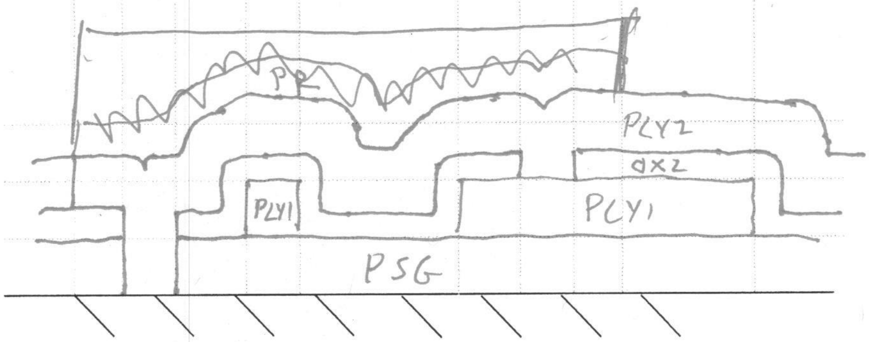
1um LPCVD PSG/ C2x

2um LPCVD poly / PLY2

No PLY2 etch – show xsection with PLY2 PR

No HF release (leave the oxides)





-1 no PR, etched poly

-2 etch through poly

-2 keep oxide

-1 square corners

a. [2] How long (in distance etched) does the etch for C2x need to be?

OX1 + OX2 = 3μm t_{OX2} only -1

b. [2] How long (in distance etched) does the PLY1 etch need to be?

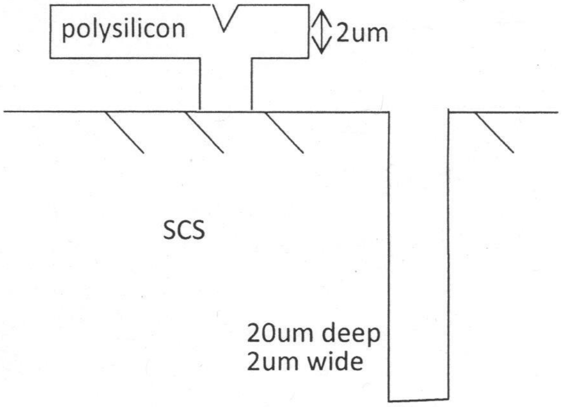
2μm

c. [2] How long (in distance etched) does the PLY2 etch need to be to avoid stringers?

$t_{PLY1} + t_{PLY2} = 4\mu m$ $t_{ply2} + t_{ox2}$ -1

Name________________________ SID________________________

5. [10] Write down a process flow that would let me make the following cross-section.



LPCVD 2 μm SiO_2 / CONT (+1)

LPCVD 2 μm Poly / POLY (+2)

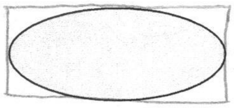
Spin PR / TRENCH (+3)

DRIE (+3)

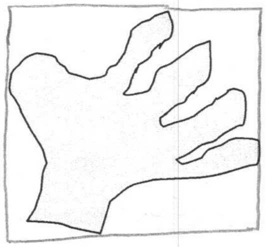
HF Release (+1)

6. [6] A (100) wafer coated with silicon dioxide has the following three 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.

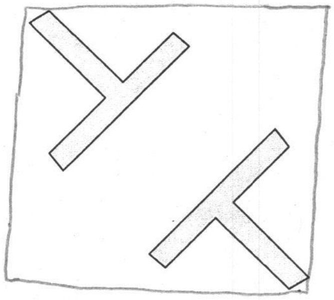
(+2)



(+2)



(+2)



7. [12 total] In a Tang, Nguyen, Howe comb drive resonator you apply 15V DC to the resonator, and 15V sin(ωt) to one of the combs. There are 100 comb gaps on each side. The suspension stiffness is 1N/m. The Q in air is 20.

   a. [6] What is the total force applied to the resonator (magnitude in N, and phase for each term)?

$$F = \frac{1}{2}\varepsilon_0 N \frac{t}{g}\left[15^2 + \frac{15^2}{2} + 2\cdot15^2\sin(\omega t) - \frac{15^2}{2}\cos(2\omega t)\right]$$

$F_{es} = 1\,nN$ @ 15V

$N = 100$

$$\underline{F = 150 + 200\sin(\omega t) - 50\cos(2\omega t)\ nN}$$

+1 pt for each phase ⊕ Mag

   b. [6] What is the total displacement of the structure if the frequency of the 15V sin wave is equal to the resonant frequency ω_n? (magnitude in m and phase for each term)

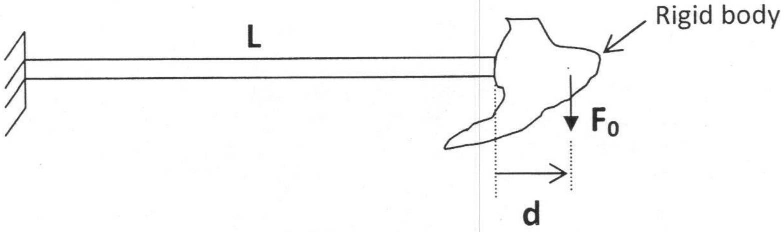
$$X(t) = \frac{150\,nN}{1\,N/m} + \frac{200^*Q}{1\,N/m}\sin(\omega t - 90^\circ)\,nN - \frac{50\cos(2\omega t - 180^\circ)\,nN}{1\,N/m\left(\frac{2\omega_n}{\omega_n}\right)^2}$$

$$\underline{X(t) = 150 + 4{,}000\sin(\omega t - 90^\circ) - 12.5\cos(2\omega t - 180^\circ)\ nm}$$

+1 pt for each phase and magnitude

Name______________________ SID______________________

8. [10 total] A beam of length **L** with transverse force and moment **F$_0$** and **M$_0$** at the tip has a tip displacement of $y(L) = [L^2M_0/2 + L^3F_0/3]/(EI)$. The beam below has a rigid body attached to the tip, and a pure transverse force F_0 applied to the rigid body at an axial distance **d** from the end of the beam. **d** may be negative.



a. [2] What is the moment M_0 on the end of the beam?

$M_0 = d F_0$

b. [4] At some value of **d**, let's call it **d$_0$**, the spring constant K becomes infinite (i.e. the tip displacement y(L)=0 for nonzero F$_0$). What is **d$_0$** in terms of **L**?

-1 missing negative

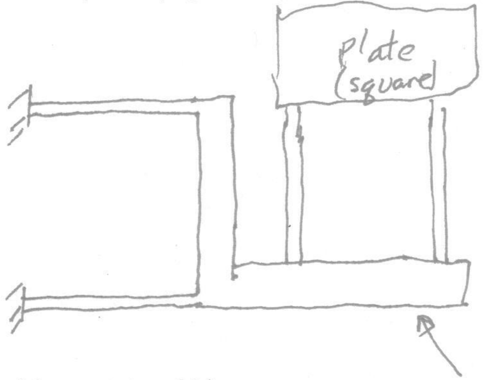
$EI\,y(L) = \frac{L^2}{2} M_0 + \frac{L^3}{3} F_0 = \frac{L^2}{2} d F_0 + \frac{L^3}{3} F_0 = 0$ $d = -\frac{2}{3} L$

c. [4] If you apply the force F$_0$ at d=d$_0$, what is the angle of the tip as a function of F$_0$?

$EI\,\Theta(L) = \frac{L^2}{2} F_0 + L M_0 = \frac{L^2}{2} F_0 - \frac{2}{3} L^2 F_0 = -\frac{L^2}{6} F_0$ $\Theta(L) = \frac{-L^2 F_0}{6EI}$

-2 didn't plug in do

9. [10] In a particular process, an end-loaded cantilever beam of length L and width b has a spring constant **K$_0$**. Design a flexure that will support a square plate such that it has a spring constant **K$_0$** in two perpendicular directions in the plane (e.g. x and y) but is relatively stiff to rotation about the normal to the plane (e.g. theta). Draw the design, and label the dimensions of important pieces.



all beams 2L long, b wide

width = 10b ⇒ 1000x stiffer

-4 stiff in x or y

-3 not stiff in θ

-2 not same in x, y

-2 missing dimensions, or no calcs

-1 wrong dimensions

Name________________________ SID________________________

10. [12 total] You have built a torsionally supported MEMS mass for a gyroscope. The torsional spring constant is $\mathbf{K_\theta}$. There is a damping factor $\mathbf{b_\theta}$. For a torsional resonator, the energy stored in the spring is $\mathbf{K_\theta\, \theta^2 /2}$, the damping torque is $\boldsymbol{\tau = b_\theta\, \omega}$, and the damping power is $P= \boldsymbol{\tau\, \omega}$.

    a. [3] What theorem describes the average angular displacement of the proof mass due to thermal noise, and what does the theorem state? Equipartion Theorem (+1)

       - Average energy in a System due to thermal noise is $\frac{1}{2}K_BT$ per degree of freedom $\underline{\overline{E}_n = \frac{1}{2}K_BT}$ (+2)

    b. [2] Write an expression for the average angular displacement of the mass due to thermal noise.

       $$\frac{1}{2}K_BT = \frac{1}{2}K_\theta\,\overline{\theta}_n^2 \qquad \boxed{\overline{\theta}_n = \sqrt{\frac{K_BT}{K_\theta}}}$$ (+2)

    c. [3] What theorem describes the power spectral density of the thermal noise exciting the system, and what does the theorem state? Fluctuation-dissipation Theorem (+1)

       - Average power injected into the system due to thermal noise is $\underline{\overline{P}_N = 4K_BT\Delta f}$ (+2)

    d. [4] Write an expression for the average torque on the structure in a 1Hz bandwidth due to thermal noise. $\tau = b_\theta\omega \qquad P = \tau\cdot\omega = \underline{b_\theta\omega^2}$ (+1)

       $\underline{\tau^2} = b_\theta^2\omega^2 = \underline{b_\theta\cdot b_\theta\omega^2}$ (+1)

       $\tau^2 = b_\theta P$

       $\tau = \sqrt{b_\theta P}$

       $\boxed{\tau = \sqrt{4K_BTb_\theta\Delta f}}$ (+2)

11. [12 total] In a piezoresistive displacement sensor, the raw output from the sensor is 100mV/μm. The 100kΩ piezoresistors are in a Wheatstone bridge. This signal goes into an amplifier with an input noise of 30nV/rt-Hz and a gain of 100.

    a. [2] What is the power spectral density of noise in the Wheatstone bridge in [W/Hz]?

       $P = 4K_BT\Delta f \qquad \boxed{\frac{P}{\Delta f} = 4K_BT}$ (+2)

    b. [4] What is the total thermal noise power spectral density at the input of the amplifier?

       $\overline{V}_{n,1K} = \frac{4nV}{\sqrt{hz}}$ (+1) $\quad \overline{V}_{n,100K} = \frac{4\sqrt{100}\,nV}{\sqrt{hz}} = \frac{40nV}{\sqrt{hz}} \quad \overline{V}_{n,tot} = \sqrt{\left(40\frac{nV}{\sqrt{hz}}\right)^2 + \left(30\frac{nV}{\sqrt{hz}}\right)^2}$ (+2) $= \boxed{50\frac{nV}{\sqrt{hz}}}$ (+1)

    c. [2] Write an expression for the output of the amplifier including both signal and noise.

       $$V_{out} = 100\left[\left(\frac{.1V}{\mu m}\right)d + 50\frac{nV}{\sqrt{hz}}\right] = \boxed{10\frac{V}{\mu m}d + 5\frac{\mu V}{\sqrt{hz}}}$$ (+1) (+1)

    d. [4] What is the smallest displacement that can be resolved in a 100Hz bandwidth by this system?

       $$10\frac{V}{\mu m}d = \frac{5\mu V}{\sqrt{hz}}\cdot\sqrt{100hz}$$

       $$10\frac{V}{\mu m}d = 50\mu V$$ (+3)

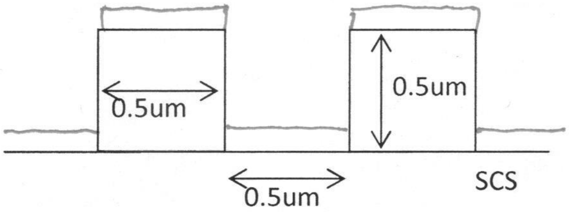
       $$d = \frac{5\mu V}{V/\mu m} = \underline{5\times10^{-12}m}$$

       $\boxed{d = 5\,pm}$ (+1)

Name______________________ SID______________________

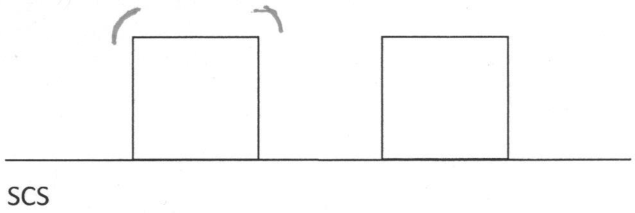
12. [12] In the following figures, assume that an SiO_2 film 0.5um thick has been patterned with a 0.5um line and space on two different silicon wafers. The cross section of two lines is shown below. Draw the expected cross-section for two different processes: 1) 0.1um evaporated aluminum 2) 0.1um LPCVD polysilicon followed by a 0.5um silicon RIE. RIE selectivity to oxide is 5:1. The substrate is single-crystal silicon. For process 2, draw the cross-section after each of the two steps.

Process 1 : 0.1um evaporated aluminum



Process 2, step 1: 0.1um LPCVD polysilicon

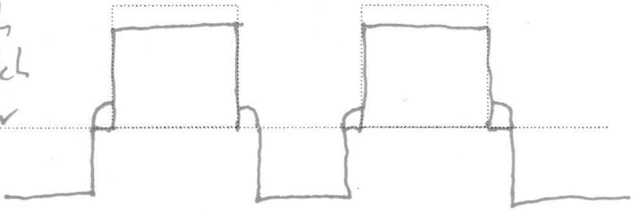
square corner -1



Process 2, step 2: 0.5um RIE silicon etch

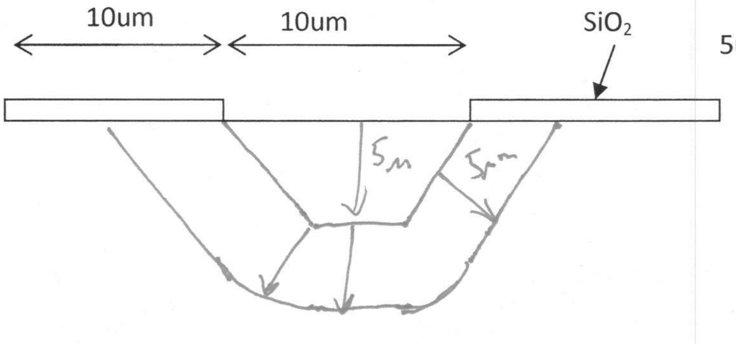
1 top
1 field
1 sidewall
1 corner

-1 missing oxide etch
-1 missing substrate etch
-1 missing poly stringer



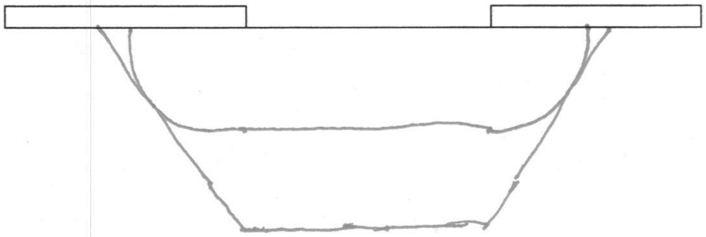
-3 isotropic

13. [12] In the following figures, a 1 micron thick SiO2 layer has been patterned to expose bare [100] silicon on two different wafers. The aperture is 10um square. Draw the cross section after each etch step for the "double etch" used on each wafer.

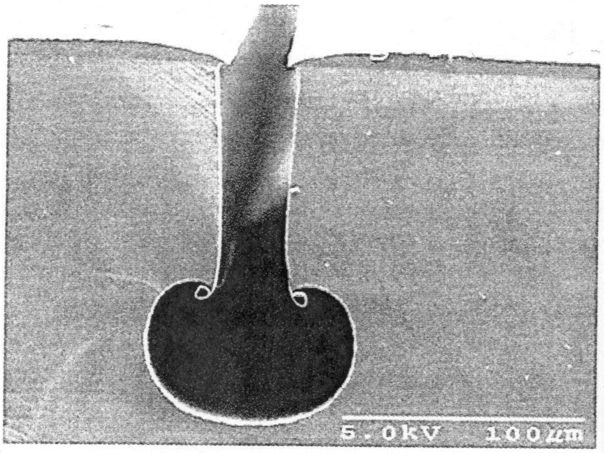


5um KOH, then 5um XeF2

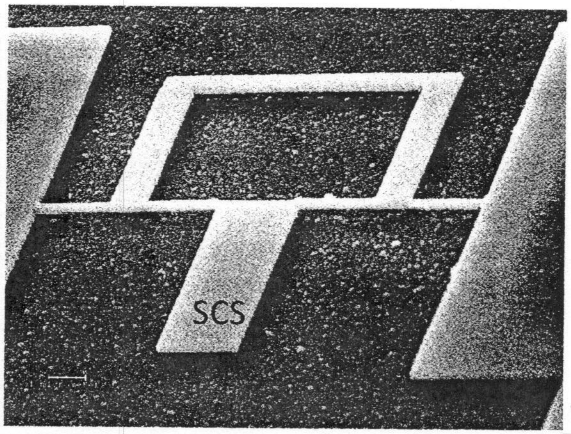
5um XeF2, then 5um KOH



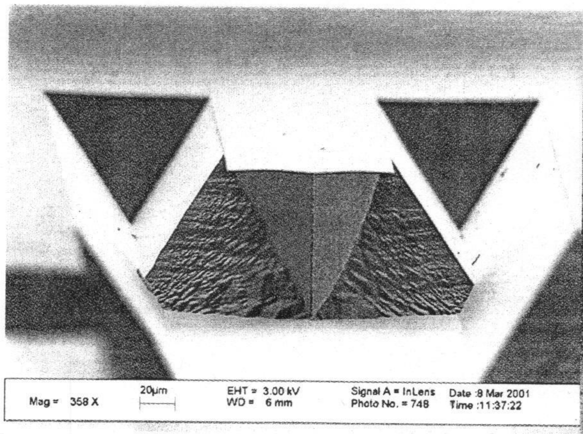
Name________________________ SID__________________________



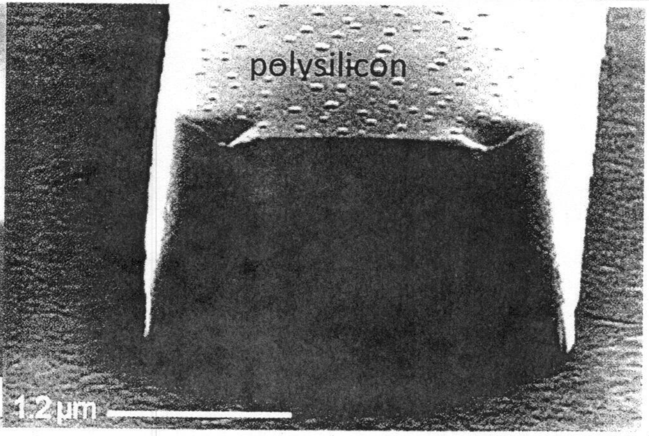
DRIE ⊕ XeF_2



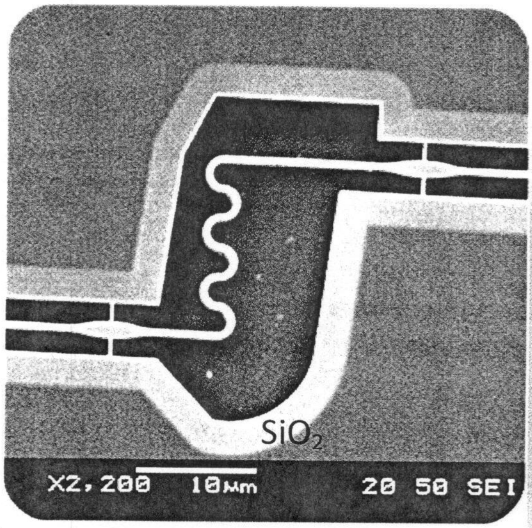
Vapor HF



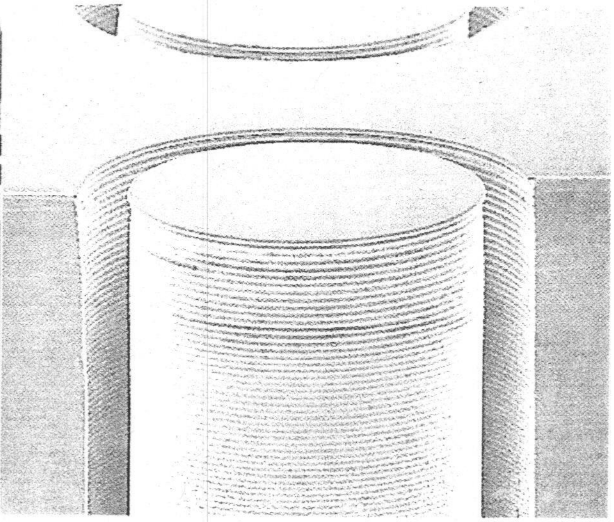
KOH



RIE



XeF_2



DRIE

14. [12] The images above were etched using one each of: KOH, RIE, DRIE, XeF2, DRIE+XeF2, Vapor HF release. Write the name of the etch next to the picture.

Images from cmi.epfh.ch , Sentech.com , Silex Microsystems, Tohoku U., http://tigger.uic.edu/~jili/robot.shtml, xactix.com (not in order)