Homework Assignment #7
Due by online submission Friday 10/27/2017 (Saturday 9am)

1. Calculate the intersection angle of all members of the \{111\} family of equivalent planes with a (110) silicon wafer.

2 pts. total, 1 pt. for each angle

Depending on the specific planes, the dot product can either be 0, 2, or -2. Specifically, this corresponds to:

\[(1 \bar{1} 1) \cdot (1 1 0) = 0\]
\[(1 1 1) \cdot (1 1 0) = 2\]
\[(\bar{1} \bar{1} 1) \cdot (1 1 0) = -2\]

There are other cases for each result. We know that the dot product will be equal to:

\[|1 1 1||1 1 0| \cos \theta\]
\[= (\sqrt{3})(\sqrt{2}) \cos \theta\]

Solving for the angles, we get

\[\theta = 90^\circ, 35.3^\circ, 144.7^\circ\]

Note that 35.3° and 144.7° are for the same plane intersection. Only counting 35.3° is enough.

2. Fold up (or just look at) a copy of the ever-popular fold-up crystal (http://www-bsac.eecs.berkeley.edu/~pister/crystal.pdf)

a. Approximately how many hours does it take to grow a 1 um thick thermal oxide at 1100C under “wet” and “dry” conditions? (note: you’ll have to extrapolate the curves a bit for one or both of these, and one of them is going to give a really long time)

2 pts. total, 1 pt. for each time

Remember that these plots are log-scale. The notches correspond to about 2x and 5x the factor of 10 below the notches. Roughly extrapolating from the curves, it looks like a 2um dry oxide will take well over 1200 minutes, or 200 hours, to grow (8.3 days!) and a wet oxide will take over 480 minutes (about 8 hours).

The big takeaway from this is that it’s very challenging to grow thick oxides in dry O2, and therefore thicker oxides are normally grown using wet oxidation processes.

b. Approximately how many hours does it take to grow a 0.1um oxide at 1000 C under wet and dry conditions?

2 pts. total, 1 pt. for each time

0.1um will take close to 3.3 hours for dry oxidation (it lands at about the first third between 100 and 1000 mins), so about 200 minutes. In comparison, it will take about 10 minutes for wet oxidation.
c. Two silicon resistors are identical in shape and both are doped with $1 \times 10^{14}$ atoms/cc, one with boron, one with phosphorous. Which one has a lower resistance? Roughly how much lower?

2 pts. total, 1 pt. for each question

Looking at the graph, we can see that the resistor doped with phosphorous will have a lower resistivity, and therefore resistance, than the one doped with boron. The resistor doped with phosphorous has a resistance about 3 times higher than the resistor doped with boron.

d. Roughly what percentage of the atoms in a crystal are dopants when silicon is doped to a resistivity of 1 m$\Omega$cm? How does this resistivity compare to the resistivity of aluminum?

2 pts. total, 1 pt. for the correct answer, 1 pt. for comparison

1 m$\Omega$cm corresponds to about $10^{20}$/cm$^3$ dopants. The silicon unit cell is 5.43 A on a side, so 160 cubic angstroms, or $1.6 \times 10^{-22}$ cm$^3$. There are 8 atoms per unit cell (to avoid double counting, 1/8 atom at each corner, 1/2 atoms at each face, 4 atoms inside the cell). This gives $8/(1.6 \times 10^{-22} \text{ cm}^3) = 5 \times 10^{22}$ atoms/cm$^3$. That means the concentration of dopants is about 0.2%.

The resistivity we doped to in this problem is: $10^{-3}$ $\Omega$cm, and the resistivity of aluminum is about $2.7 \times 10^{-6}$ $\Omega$cm. After doping the silicon, its resistivity is still three orders of magnitude higher than that of aluminum.

3. In the following figure, assuming that the cantilever pointing out of the page is oriented in the [110] direction on a (001) wafer, label each flat etch face in the image.
(image source: https://cmi.epfl.ch/etch/PladeKOH.php)
The etch faces are numbered on the image above. Notice that 1&6, 2&7, and 3&8 share the same etch face.

The etch faces are:
- 1,6: (111)
- 2,7: (111)
- 3,8: (111)
- 4: (100)
- 5: (010)
- 9: (001)

4. In Figure 3 and Table VI of “What is the Young’s modulus of silicon?” [4]

3 pts. total, 1 pt. per part

a. How much does the spring constant of a beam vary as the orientation of the axis of the beam rotates 45 degrees on a (100) wafer?

The Young’s modulus varies from 130GPa in the <100> direction to 169GPa in the <110> direction. This is equivalent to a 30% change. Since the spring constant is directly proportional to the Young’s modulus, the value for k, the spring constant, will also vary by 30%.

b. How does the stiffness of a beam change if the temperature increases by 100°C?

We can use Table VI to find the temperature coefficient of E, which is about -60 ppm/°C. If the temperature increases by 100°C, the Young’s modulus will increase by 6,000ppm, or 0.6% (a percent is 10,000 parts per million). As with part a, the spring constant is directly proportional to the Young’s modulus. That means that k, the spring constant, will also increase by 0.6%.

c. What is the torsional spring constant in axial twisting of a 1mm long, 2µm wide beam in 25µm SOIMUMPS?

The torsional spring constant of a straight beam of length L and cross-section ab, where a<<b, is given by the equation:

\[ k_\theta = \frac{\text{torque}}{\theta} = \frac{JG}{L} \]

where the angle \( \theta \) is the angle of rotation of the beam.

The value of \( J \) is defined by:

\[ J = ca^3b \]

where the constant c is dependent on the aspect ratio of the beam. When a<<b, c is approximately 1/3. In this case, a is 2µm and b is 25µm. We are safe enough to use that value of c.

We can also find the Young’s modulus for a twisting beam to be 50.9GPa (Table VI). Plugging in the values to solve for the spring constant, we obtain:

\[ k_\theta = 3.4 \times 10^{-9} \frac{Nm}{rads} \]
5. In reference [1],

6 pts. total

a. In the paragraph below Figure 2 it explains why the pressure rises during the etch. Based on that explanation, approximately what fraction of the XeF2 gas is consumed in the etch shown in Figure 2?

1 pt. for the approximately correct answer

The initial pressure is about 0.75 torr. The XeF2 gas will be fully consumed when the final pressure is about (3/2) the initial pressure:

\[
\frac{3}{2} P_{\text{initial}} = 1.125 \text{ torr}
\]

Knowing this, we can make a linear fit with our values and find what percentage of the XeF2 gas was consumed during the etch.

Therefore: after the etch, the pressure is about 0.91 torr, which corresponds to about 43% of the gas consumed.

b. Compare the lateral etch rate of bulk silicon and polysilicon thin films (figures 6 and 11) with 60 second pulses and 120 second pulses. (n.b. check the number of pulses used in each etch). Are they both linear in the length of the pulse? Are the rates the same?

1 pt. for saying whether or not they are each linear, 1 pt. for the etch rate comparison at 60s

Figure 11 shows the polysilicon thin film lateral etch rate, which is roughly linear with the length of the pulse. Figure 6 shows the bulk silicon thin film lateral etch rate. For this case, the etch rate is definitely not linear with the length of the pulse.

The etch rates are about the same for a 60 second pulse. However, after that, the bulk silicon etch rate slows down as the length of the pulse increases, while the polysilicon etch rate continues to increase linearly with the length of the pulse.

c. In figure 8, which structures etched fastest in the first two pulses, the 50µm, 200µm, or 800µm square openings? What about after 12 pulses? What might account for the difference, and the shape of the etch front of the 800µm aperture after 12 pulses?

1 pt. for the correct answer at two pulses
1 pt. for the correct answer after 12 pulses
1 pt. for an explanation on what causes the difference

In figure 8, the structures etched fastest in the first two pulses are the 50µm box and the 200µm box. After 12 pulses, the 200µm box and the 800µm box etch the fastest.

Even though the exact answer is unknown, the difference could be caused by two things. For the 800µm box, the faster etching in the corners than in the middle might be caused by a depletion of reactants around the center. Furthermore, the faster etching in the larger boxes may occur because the etching in the smaller box is diffusion limited.

6. In reference [2],

3 pts. total, 1 pt. per part

a. From Figure 5, what is the highest etch rate that they measured in the “smooth etched surface region”? Roughly what is the mixture of acids that gives that etch rate?
The highest etch rate they measured in the “smooth etched surface region” is 23.6µm/min. Roughly, this corresponds to 40% HF (49%), 60% HNO₃ (69%), and 0% CH₃COOH.

b. Same question, but for the lowest etch rate in that region.

The lowest etch rate they measured in the “smooth etched surface region” is 2.9µm/min. Roughly, this corresponds to 10% HF (49%), 83% HNO₃ (69%), and 10% CH₃COOH.

c. At the overall highest etch rate that they measured, how long would it take to etch a 500µm thick bare silicon wafer (both sides exposed to the etch).

The overall highest etch rate they measured was 609.8µm/min. It would take about 25 seconds to etch the wafer. Since both sides are exposed to the etch, only 250µm would have to be etched per side.

7. In reference [3], rectangular apertures aligned with the flat of a (100) wafer, or 45 degrees to the flat, are etched in KOH (they also did NaOH etching, but you can ignore that for this problem).

7 pts. total

a. In Figure 2, what is the direction of the aperture alignment (either <100> or <110>)? What is the resulting sidewall angle and plane?

2 pts. total, 1 pt. for the direction, 1 pt. for the resulting angle and plane

In figure 2, the direction of the aperture alignment is <110>, since they are aligned with the wafer flat, which is specified to be <110>. The resulting sidewall angle is 54.7°, and the plane is the {111} plane.

b. In Figure 3, what is the direction of the aperture alignment? What are the resulting sidewall angles and corresponding planes? What process variable determines plane emerges?

3 pts. total, 1 pt. for the direction, 1 pt. for the resulting angle and plane, 1 pt. for the process variable

In figure 3, the direction of the aperture alignment is <010>. The resulting sidewall angles are 45° for the {110} plane, and 90° for the {100} plane. The process variable in this case is the KOH concentration in wt. %. Another process variable could be surface tension (you can mark your answer correct if you said surface tension instead of KOH concentration).

c. In Figure 5, cross-sections AA and BB are on the wafer with the standard CMOS orientation and flat. Other than ~54 degrees, what other sidewall angles are possible, what combination of mask layout and processing is necessary to get them, and what crystal planes define them?

2 pts. total, 1 pt. per correct angle, combination of masks, etc.

The question is asking about cross-sections AA and BB, so we can ignore the other cross-sections in the figure. The other possible sidewall angles are:

90° for a {100} wafer with a <110> primary flat orientation, layout features aligned in the <110> or <1T10> directions, and the crystal planes that define them are {100}.

45° for a {100} wafer with a <110> primary flat orientation, layout features aligned in the <010> directions, and the crystal planes that define them are {110}.
8. [247A] Flip through at least one MEMS journal or conference proceedings from cover to cover (the library has journals, the bsac conference room 402 Cory has journals and conference proceedings and is open during the day, the internet will work too). Find at least two papers where either:
   a. the design or structure could have been built in a standard process but wasn’t
   b. some aspect of the paper could be extended, refined, clarified, or otherwise improved by designing and testing structures in a standard process

5 pts. for appropriate effort


