EE 147/247A Prof. Pister
Fall 2020

Homework Assignment #6

Due on bcourses Wednesday 10/21/2020 (zero credit after 9 AM Thursday)

1. [4 pts] Take a look at https://www.digikey.com/en/articles/use-mems-rf-switches-to-solve-advanced-wireless-design-and-integration-issues
   a. What material is the MEMS switch made out of (Figure 3)?

      [1] Gold (Full points for Silicon and Gold)

   b. How many dice are in the ADGM1004 package (Figure 5)?

      [1] 3 die. Give yourself full credit for "2 die", but look carefully at the figure, and read the caption.

   c. How many cycles is the switch capable of before failure? If it switches once per second, how many years would it last?

      [1] One billion cycles!

      [1] ~30 years

2. [3 pts] The MEMSIC thermal accelerometer was perhaps the cheapest accelerometer on the market in 2003. http://itersnews.com/wp-content/uploads/experts/2016/05/103071mentorpaper_95764.pdf
   a. If the MEMS cavity in Figure 2 is 1mm2, how big is the die in Figure 3 (which includes all of the CMOS interface electronics)

      [1] Looks about 2-3mm on a side so $4 - 9mm^2$

   b. How much did the chip cost to manufacture if die area costs $0.05/mm2?

      [1] $0.20-$0.45

   c. The lower right of Figure 2 shows the silicon cavity etched into the substrate, with the accelerometer removed. The etch looks mostly isotropic (you can see hints of the structure in the etch shape). This etch needed to be selective to silicon dioxide (that's what the accelerometer structure is mostly made of), what etchant did they most likely use?

      XeF_2

      [1] (it will selectively etch Si with respect to SiO_2, Photoresist and Aluminum)

3. [9 pts] In Go & Pohlman (reference [1]), they plot measured breakdown voltage vs. electrode gap for many different MEMS structures. The data are taken from many different research papers. As they write, "Fig. 3 highlights the complexity of breakdown at the microscale, where general trends are common but quantitative data are heavily dependant on the electrode geometry, material, and surface roughness."
   a. In Figure 3, given all of the different data sets, what is the largest safe voltage (no breakdown in any data set) with a 5um gap? With a 1um gap?

      [2] 1um: 120V and for 5um: 10V

   b. In Figure 4c, the data sets from references 19 and 24 are for silicon-silicon gaps, which generally have higher breakdown voltages than metal-metal or silicon-metal gaps. For those two data sets, what is the largest safe voltage with a 5um gap? With a 1um gap?

      [2] 1um: 400V and for 5um: 300V

   c. From Figure 4c, make a table for the data from reference 19, with a column for the gap, the breakdown voltage, and an estimate the electric field at which the devices broke down. Compare to the macroscopic breakdown field for air, 3MV/m.

   [4] 1 point for each column, and 1 point extra if you actually got mostly the right answers!

Gap	Breakdown Voltage	Breakdown Electric Field
1um	625V	$625M\frac{V}{m}$
2um	400V	$200M\frac{V}{m}$

2.5um	390V	$156M\frac{V}{m}$
4um	325V	$81M\frac{V}{m}$
5um	300V	$60M\frac{V}{m}$
6um	325V	$54M\frac{V}{m}$
7um	310V	$45M\frac{V}{m}$

As you can see, the breakdown electric field for micron-sized gaps is an order of magnitude or more greater than it is for air at a macroscopic level.
[1] Give yourself a point if you said anything like that.

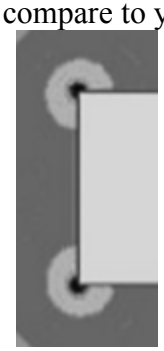
4. [4] In reference [24] from the previous paper
   a. Compare the failure modes in Figures 1 and 2. Both are likely to be permanently fatal to device operation. Which material looks worse?

[1] Figure 2 looks worse. It's likely due to the lower melting point of Aluminum compared to Silicon. The Aluminum is vaporized when the lightning bolt occurs at breakdown.
Full Points for any honest attempt here

   b. For the comb drive field simulation in Figure 8, where is the electric field the largest?

[1] The corners of the beam have the highest electric field

   c. How do the field plots in Figure 8 compare to your calculations above?



[2] For a 5um gap I calculated a breakdown electric field of ~$60M\frac{V}{m}$ and Figure 8 shows a simulated electric field of ~$63M\frac{V}{m}$ for a 5um gap. Matches nicely!

1 point for doing some comparison, 1 more point if it's right.

5. [5 pts] Calculate the intersection angle of all members of the {111} family of equivalent planes with a (110) silicon wafer.
   1 point for knowing which formula to use.
   1 point each for figuring out that the dot product can be 0, 2, or -2 (3 points total)
   1 point for being able to do match and get the right answer

Depending on the specific planes, the dot product can either be 0, 2, or -2. Specifically this corresponds to $(1\,\bar{1}\,1)\cdot(1\,1\,0)=0, (1\,1\,1)\cdot(1\,1\,0)=2$ and $(\bar{1}\,\bar{1}\,1)\cdot(1\,1\,0)=-2$. 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

$$\theta = 90°, 35.3°, 144.7°$$

6. [8 pts] 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] dry: more than 1000 minutes (full credit for anything between 1,000 and 10,000) compared to wet: 100 minutes (dry oxide is better for CMOS gates and is a Huge reason why silicon won out in the semiconductor industry but it takes a loooong time to grow)

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

[2] dry: 200 minutes (100 to 200 OK) compared to wet: 10 minutes

c. [2] Two silicon resistors are identical in shape and both are doped with 1e14 atoms/cc, one with boron, one with phosphorous. Which one has a lower resistance? Roughly how much lower?

1 point for saying phosphorous, 1 point for an answer between 3 and 5 times lower

Phosphorous has the lower resistance by ~3x

2=log(Boron Resistivity)→ Boron Resistivity =100ohm-cm and

1.5=log(Phosphorous Resistivity))→ Phosphorous Resistivity=33ohm-cm

d. [2] Roughly what percentage of the atoms in a crystal are dopants when silicon is doped to a resistivity of 1mΩcm? How does this resistivity compare to the resistivity of aluminum?

On the graph 1mOhm-cm corresponds to -3 so there are $10^{20}\,\frac{atoms}{cm^3}$

Silicon has $5 * 10^{22}\,\frac{atoms}{cm^3}$ so that's $\frac{1}{500} = 0.2\%$

The resistivity of Aluminum is 2.8μOhm-cm which is ~350x smaller than $10^{20}\,\frac{atoms}{cm^3}$ doped Si

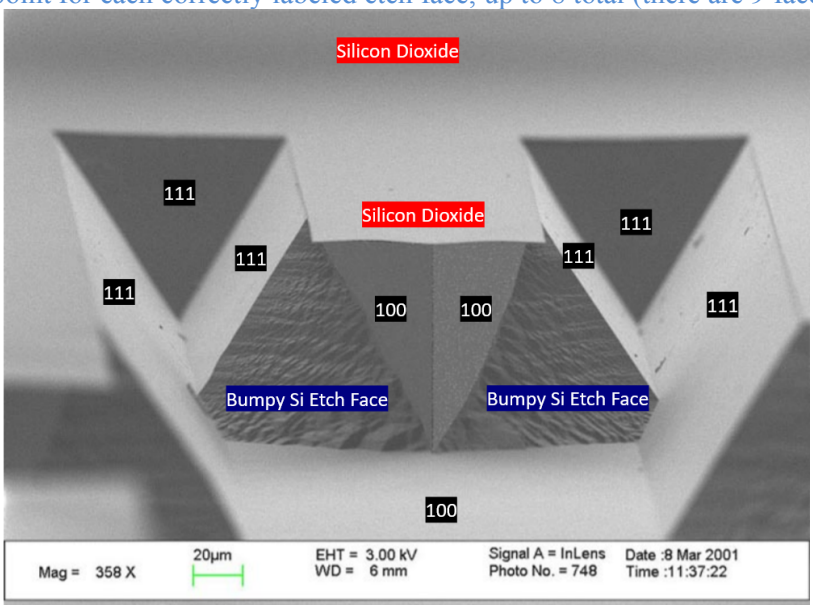
1 point for 0.2%

1 point for saying that even heavily doped silicon is much higher resistivity than aluminum

7. [8 pts] 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 Silicon Dioxide is not an etch face. It is labeled to help you understand the picture. The 100 and 111 planes are the only that need to be labeled.

1 point for each correctly labeled etch face, up to 8 total (there are 9 faces)



[1] Go, Pohlman, "A mathematical model of the modified Paschen's curve for breakdown in microscale gaps", J. Applied Physics, 2010.
[24] Chen, Yeh, Wang, "Electrical breakdown phenomena for devices with micron separations", J. MM