1. You have a phosphorous-doped N-type wafer with a resistivity of 10 Ohm-cm. You ion implant Boron at an energy of 30keV and concentration of \( Q = 1 \times 10^{15} \text{ atoms/cm}^2 \). You then anneal/diffuse at 1050C for 1 hour.

   a. What is the average distance that the boron ions travel into the crystal? (Figure 5.3)

   **Solution:** 1 pt.
   
   \( 0.1 \text{um} \)

   b. What is the standard deviation of that distance? (Figure 5.3)

   **Solution:** 1 pt.
   
   \( 0.035 \text{um} (\pm 0.005 \text{um ok}) \)

   c. Estimate the peak concentration of boron in the implanted region (Eqn 5.6)

   **Solution:** 1 pt.
   
   \[
   Q = \sqrt{2\pi N_p \Delta R_p} \to N_p = \frac{Q}{\sqrt{2\pi \Delta R_p}} \\
   N_p \approx 1 \times 10^{20} \text{cm}^{-3}
   \]

   d. What is the phosphorous concentration in the wafer? (Figure 4.8)

   **Solution:** 1 pt.
   
   \( 4.5 \times 10^{14} \text{ cm}^{-3} (\pm 1 \times 10^{14} \text{ ok}) \)

   e. What is the diffusion coefficient of Boron in silicon at 1050C? (Jaeger Figure 4.5)

   **Solution:** 1 pt.
   
   \( 10^{-13} \text{ cm}^2/\text{s} (\pm 50\% \text{ ok}) \)

   f. Using equation 4.6 in Jaeger section 4.2.2, and assuming that the distribution of Boron due to ion implantation is shallow enough that it can be modeled as a dose \( Q \) at the surface of the wafer, plot the concentration vs. depth in the silicon for various diffusion times

   - use a log scale for the vertical axis, from 1e14 to 1e20
   - use a linear horizontal axis from 0 to 2 um

   **Solution:** 1 pt.
g. How long does it take for the surface concentration calculated from part f to be less than the implant does divided by the average implant depth? (this is a very rough estimate of when the simulation in part f becomes starts to be a useful approximation of the diffusion profile)

Solution: 1 pt.

\[ \frac{1 \text{e}15 \text{cm}^{-2}}{0.1 \text{um}} = 1 \text{e}20 \text{cm}^{-3} \]

Changing the diffusion time in the plot, it takes about 313 seconds for the concentration to fall below 1e20 cm^{-3}

h. What is the depth of the junction between P and N type regions?

Solution: 1 pt.

From the plot, it looks like the boron impurity concentration equals the background phosphorous impurity concentration at 1.35 um

2. You have a P-type substrate with a doping concentration of 1e16. You would like to have an N-well with a surface concentration of 5e16 and a junction depth of 2um. Design the process for creating the N-well. Specifically, choose ion implantation species, energy, and dose, and diffusion temperature and time.

Solution: 1 pt. for each of species, energy, dose, temperature, time, 1 pt. for reasonable justifications (6 pts. total)

From the two points of the impurity concentration that we are aiming for (5e16 at the surface, 1e16 impurity concentration at 2um) we can find the diffusion and time product from the Gaussian distribution (limited source) (Equation 4.9)

\[ \sqrt{D \cdot t} = \frac{x_f}{2 \sqrt{\ln \left( \frac{N_a}{N_B} \right)}} = \frac{0.0002 \text{ cm}}{2 \sqrt{\ln \left( \frac{5 \text{e}16}{1 \text{e}16} \right)}} = 7.9 \times 10^{-5} \text{ cm} \]

We can solve for the dose \( Q \) with this result (Equation 4.6)

\[ Q = \sqrt{\pi D \cdot t} N(0, t) = \sqrt{\pi} \left( 7.9 \times 10^{-5} \text{ cm} \right) \left( 5 \text{e}16 \text{ cm}^{-3} \right) \]

\[ Q \approx 7 \text{e}12 \text{ cm}^{-2} \]

Choosing a guess at a diffusion time of 1 hour, we get a diffusion coefficient of 1.7e-12 cm^2/s. For phosphorous, an n-type dopant, this happens at a temperature of about 1200C (Figure 4.5). (note that 1200C is hotter than we usually like to run our furnaces, so it is more likely that we'd pick a longer time and a lower temperature, like ~24 hours and 1100C.) For an implantation energy of 30keV, we get an average depth of 0.03um (Figure 5.3), and these approximations become reasonably valid when the surface concentration falls below \( Q/0.03 \text{um} = 2.3 \text{e}18 \text{ cm}^{-3} \). Plotting the concentration vs. the depth, this is true after about 1.5s. Our diffusion time of an hour is reasonably valid.

The plot below shows the diffusion profile after various times.

Species: Phosphorous
Energy: 30keV
Dose: 7e12 cm^{-2}
Temperature: 1200C
Time: 1hr
3. Referring to the CMOS-MEMS powerpoint presentation on the course website,
   
a. What is the material etched, and what defines the region to be etched, in the figure on slide 4? What materials can be included in the remaining structures?

   Solution: 1 pt. for material etched, 1 pt. for mask, 1 pt. for remaining structure (3pts. total)
   Material etched: Silicon, Mask: Oxide/metal stack and an electrochemical etchstop
   Structure: Oxide/metal CMOS stack

   b. What is the material etched, and what defines the region to be etched, in Figure b on slide 5? Figure c? Figure d? What materials can be included in the remaining structures?

   Solution: Same as part a, mask and etched material for each figure (7 pts. total)
   Fig. b - Materials etched: Oxide (anisotropic), Mask: Metal
   Fig. c - Materials etched: Silicon (anisotropic), Mask: Metal/Oxide stack
   Fig. d – Materials etched: Silicon (isotropic), Mask: Metal/Oxide stack
   Remaining structural material: Oxide/metal stack

   c. What is the material etched, and what defines the region to be etched, in Figure b on slide 7? Figure c? Figure d? What materials can be included in the remaining structures?

   Solution: Same as part a, for each figure (7 pts. total)
   Fig. b - Materials etched: Metal (isotropic), Mask: Passivation layer
   Fig. c - Materials etched: Passivation layer, Mask: None (blanket etch)
   Fig. d – Materials etched: Silicon (isotropic), Mask: Metal/Oxide stack
   Remaining structural material: Oxide/metal stack

   d. What is the material etched, and what defines the region to be etched, on slide 9? What materials can be included in the remaining structures?

   Solution: Same as part a (3 pts. total)
   Materials etched: Oxide (anisotropic), Mask: Aluminum
   Remaining structural material: Aluminum

4. Referring to the Invense-Nasiri powerpoint presentation on the course website, how would you design a simple capacitive accelerometer designed to be packaged in vacuum? I’m not interested in the details of what the spring, mass, and comb fingers look like, but rather where those features are relative to the CAVITY mask, and how the wiring gets underneath the seal ring and makes electrical and mechanical
connection between structure and CMOS, using STANDOFF and GERMANIUM on the MEMS wafer, and MET5 on the CMOS wafer (representing the top level metal). Draw those masks.

Solution: 1 pt. for proper MET5 seal ring, 1 pt. for proper GERMANIUM seal ring, 1 pt. for correct STANDOFF mask, 1 pt. for doing contact pads correctly (inside vacuum encapsulation) (4 pts. total)