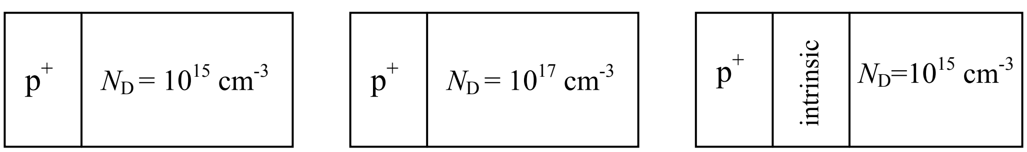
ECSE-2210 Microelectronics Technology
Class Activity 15 – Solution

1. Consider a planar p^+-n Si step junction diode with an n-side doping of $N_D = 10^{15}$ cm^{-3} at $T = 300$ K.
   a. Estimate the approximate breakdown voltage V_B of the diode.
   You have to read this off from figure 6.11 in the textbook on page 263. Read the value corresponding to the Si curve at a doping of $N_D = 10^{15}$ cm^{-3}
   $V_B \approx 320$ V

   b. Calculate the depletion layer width at the breakdown voltage estimated above.
   $W = [2\varepsilon_{Si} / (q\, N_D) \times (V_{bi} - V_A)]^{1/2}$
   $= [2 \times 10^{-12} \times (320) / (1.6 \times 10^{-19} \times 10^{15})]^{1/2}$
   $= 20$ μm
   Note: Neglect V_{bi} compared to V_A of 320 V

   c. Calculate the maximum value of the electric field in the depletion region at breakdown.
   $|\mathcal{E}_{max}| = |\mathcal{E}(0)| = (q\, N_D / \varepsilon_{Si}) \times x_n \approx (q\, N_D / \varepsilon_{Si}) \times W = 3.13 \times 10^5$ V/cm
   ***Note*:** Since p^+-n junction $x_p << x_n$, most of the depletion region extends into the n-region and $W \approx x_n$

2. Consider three p^+-n junctions as shown below. Which one will have the highest breakdown voltage? Which one will have the lowest breakdown voltage? Which one will have the highest R-G related current ($I_{R\text{-}G}$) at reverse bias? (Try to understand the physical reasoning).



The last one will have the highest breakdown voltage. Since the intrinsic region adds to the depletion layer width, we can apply more voltage before the maximum $\mathcal{E}$-field reaches the critical $\mathcal{E}$-field, $\mathcal{E}_{cr}$.
$W = [2\, \varepsilon_{Si} / q\, N_D \times (V_{bi} - V_{BR})]^{1/2}$
We see that the breakdown voltage is directly proportional to the depletion region width. As the width increases, the breakdown voltage increases quadratically.

The middle one will have the lowest breakdown voltage since the $\mathcal{E}$-field will reach the critical value at lower voltage. Note that the area of $\mathcal{E}$-vs.-x curve corresponds to voltage, so the middle one can withstand lower voltage for a given critical field.
We see that the middle diode has the least depletion region width. As a result it has the least breakdown voltage.
The last one will have the highest $I_{R\text{-}G}$ since it will have the highest volume for the depletion layer, (wider W). $I_{R\text{-}G}$ is directly proportional to W.

3. Consider the following Si p-n junction at 300 K. Assume the junction area is $A = 1\text{cm}^2$.

p-side	**n-side**
$N_A = 10^{16}\ \text{cm}^{-3}$	$N_D = 10^{16}\ \text{cm}^{-3}$
$D_n = 25\ \text{cm}^2/\text{s}$	$D_p = 10\ \text{cm}^2/\text{s}$
$\tau_n = 5 \times 10^{-7}\ \text{s}$	$\tau_p = 5 \times 10^{-7}\ \text{s}$
$\tau_0 = 5 \times 10^{-7}\ \text{s}$	

a. Calculate the ideal reverse saturation current at –5 V reverse bias.
First find L_n and L_p; then find n_{p0} and p_{n0}
$L_n = (25 \times 5 \times 10^{-7})^{1/2} = 35.3\ \mu\text{m}$ (p-side)
$L_p = (10 \times 5 \times 10^{-7})^{1/2} = 22.3\ \mu\text{m}$ (n-side)
$n_{p0} = n_i^2 / N_A = 10^4\ \text{cm}^{-3}$ (p-side)
$p_{n0} = n_i^2 / N_D = 10^4\ \text{cm}^{-3}$ (n-side)

Use standard expression for I_0:
$I_0 = q\,A\,D_p/L_p \times p_{n0} + q\,A\,D_n/L_n \times n_{p0} = 1.85 \times 10^{-11}$ A.

b. Calculate the generation-recombination current at –5 V reverse bias. Note that this current is many orders of magnitude higher than the expected ideal reverse current for Si diodes. Diodes fabricated on lower band gap materials obey the ideal diode behavior more closely.

First find the depletion layer width.

$$W = \left[\frac{2K_s\varepsilon_0}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)(V_{bi} - V_A)\right]^{1/2}$$

$W = 1.11\ \mu\text{m}$
***Note*:** Neglect V_{bi} compared to 5 V.

$I_{R\text{-}G} = (q\,A\,n_i\,W) / 2\tau_0 = 1.77 \times 10^{-7}$A.
***Note*:** This value is much higher than the "ideal" value.

4. Suppose $I_0 = 10^{-14}$ A and $R_s = 2\ \Omega$ in a diode at $T = 300$ K when high-level injection is negligible. Suppose you want to pass 50 mA through the diode.

a. Determine the voltage that has to be applied (V_A) to the diode to get the above current. (Hint: Calculate the junction voltage V_J and the voltage drop due to the series resistance)

At the desired I value, $I\,R_s = 50 \times 10^{-3} \times 2 = 0.1$ V
$V_A = V_J + I\,R_s$
$V_A = 0.757\ \text{V} + 0.1\ \text{V} = 0.857\ \text{V}$

b. Suppose the diode series resistance is 20 Ω, and you applied the voltage you got in part (a). What will be the current through the diode? Note the effect of parasitic series resistance on the diode current. (Hint: You will end up with an equation for I that cannot be easily solved. Use trial and error method to obtain the proper I value from this equation).

Now the applied voltage is 0.857 V. Some voltage will drop across the parasitic series resistance, and the actual junction voltage will be $V_J = V_A - I R_S$.
Solving by trial and error method, we get I = 1 mA. See the drastic reduction in the current.