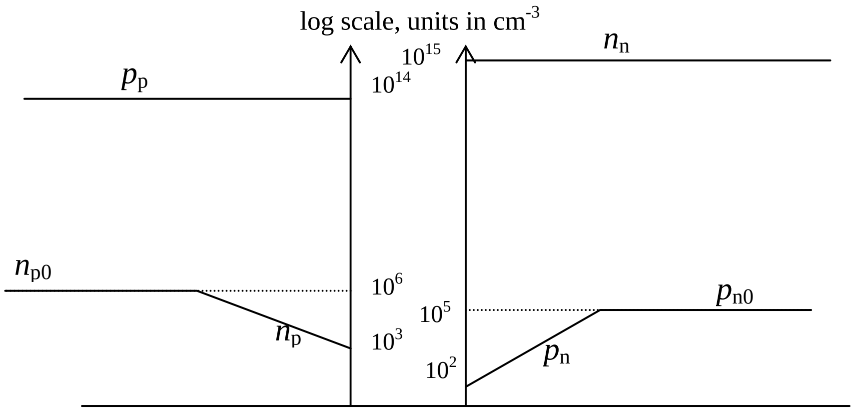
ECSE-2210 Microelectronics Technology
Homework 5 – Solution

1. (Problem 6.10 in text). The figure below is a dimensioned plot of the steady state carrier concentration inside a p-n junction diode at 300 K.
   a. Is the diode forward biased or reverse biased? Explain.
   b. Do low-level injection conditions prevail in the quasi-neutral regions? Explain.
   c. What are the p-side and n-side doping concentrations?
   d. Determine the applied voltage, V_A.



Solutions:

a. Reverse. The minority carrier concentration at the edge of the depletion layer is less than the equilibrium value. Definitely, carriers are not injected across the junction as in the forward biased case.
b. Yes. The majority carrier concentration did not change anywhere in the neutral region.
c. Doping on the p-side is $N_A = 10^{14}$ cm^{-3} and on the n-side is $N_D = 10^{15}$cm^{-3}. You can read off the majority carrier concentration from the graph.
d. The applied voltage is V_A
   $p_n(0)/p_{n0} = \exp(qV_A/kT) \rightarrow V_A = -0.178$ V (Reverse bias)

2. An abrupt silicon p-n junction diode has the following characteristics. P-side: N-side:

   $N_A = 10^{16}$ cm^{-3} $N_D = 4 \times 10^{16}$
   $\mu_n = 1000$ cm^2/Vs $\mu_p = 350$ cm^2/Vs
   $\tau_p = 10^{-7}$sec $\tau_p = 10^{-7}$sec
   Area $A = 10^{-2}$ cm^2

   Calculate the following (a-d) quantities:
   (a) Reverse saturation hole current component.
   (b) Reverse saturation electron current component.
   (c) Minority carrier concentrations at the edge of the depletion layer, $n_p(0)$ and $p_n(0)$, for a forward voltage of 0.6 V.
   (d) Electron and hole current for the bias condition of (c).
   (e) Make a rough sketch of the minority carrier concentration profile in the quasi-neutral regions for the bias condition of (c).
   (f) Suppose the forward voltage is increased to a value such that the injected minority carrier concentration at the n-side depletion layer edge is equal to the doping concentration (i.e., 4×10^{16} cm^{-3}). Calculate this forward voltage. Compare this voltage to the built-in voltage. Comment on the results.
   (g) Suppose the critical electric field at breakdown for this diode is 10^6 V/cm, and then calculate the breakdown voltage of this diode.

Solution:

First find D_p, L_p, D_n, L_n, p_{n0} and n_{p0}

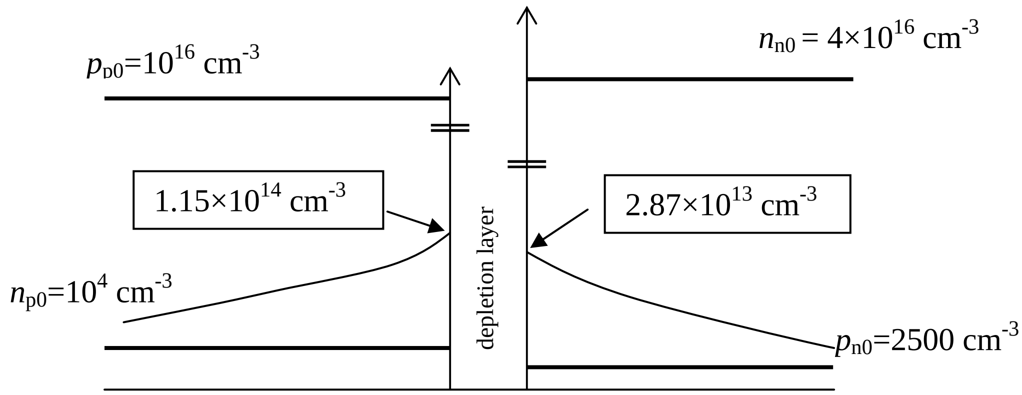
$D_p = (kT/q) \times \mu_p = 9.1$ cm^2/s; $D_n = 25.9$ cm^2/s
$L_p = (D_p \tau_p)^{1/2} = 9.5 \times 10^{-4}$ cm; $L_n = 1.61 \times 10^{-3}$ cm.
$p_{n0} = n_i^2/N_D = 2500$ cm^{-3}; $n_{p0} = n_i^2/N_A = 10^4$ cm^{-3}.

a. $I_{p0} = qA(D_p/L_p)p_{n0} = 3.8 \times 10^{-14}$ A

b. $I_{n0} = qA(D_n/L_n)n_{p0} = 2.57 \times 10^{-13}$ A

c. $n_p(0) = n_{po} \exp(qV_A/kT) = 1.15 \times 10^{14}$ cm^{-3}
   $p_n(0) = p_{no} \exp(qV_A/kT) = 2.87 \times 10^{13}$ cm^{-3}.

d. $I_p = 3.8 \times 10^{-14} \exp(qV_A/kT) = 4.37 \times 10^{-4}$ A
e. $I_n = 2.57 \times 10^{-13} \exp(qV_A/kT) = 2.95 \times 10^{-3}$ A



f. We want $p_n(0) = N_D = 4 \times 10^{16}\text{cm}^{-3}$; $p_n(0)/p_{n0} = \exp(qV/kT)$
i.e., $V = 0.787$ V

Comments: First of all, this is no longer low-level injection. So, these formulae are not applicable. Second, at this high forward voltage, the parasitic series resistances play a role, and the actual junction voltage will be less than the applied value. Otherwise, when the applied voltage is more than the built-in voltage, there will be infinite current flow.

g. The maximum electric field in a p-n junction is given by the equation 6.36. (or you can use equation 5.21 or others knowing that the maximum $\mathcal{E}$-field occurs at $x = 0$. See graph 5.9. Equations 5.30 gives the relationship between x_n and V_{bi}).

Now, Ignore V_{bi} since V_A is large at breakdown. $\varepsilon = 10^{-12}$ F/cm; $N_A = 10^{16}$ cm^{-3},
$N_D = 4\times10^{16}$ cm^{-3}; $\mathcal{E} = 10^6$ V/cm (given);
Solving for V_A we get, $V_A = 390$ V.