KEY for Test 2, Summer 2015

T = 300K for all problems.

1. (10 points) A Si sample is doped with 10^{16} donor atoms/cm^3. At 300K, what is the hole concentration and where is the Fermi level relative to the intrinsic energy level (mid-gap)?

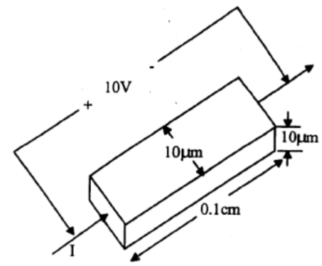
$$N_d = 10^{16} cm^{-3} \approx n_o$$

$$p_o = \frac{n_i^2}{n_o} = \frac{2.25x10^{20} cm^{-6}}{10^{16} cm^{-3}} = 22{,}500 cm^{-3}$$

$$\text{From } n_o = n_i e^{(E_F - E_i)/kT}$$

$$(E_F - E_i) = kT ln\left(\frac{n_o}{n_i}\right) = 0.347 eV$$

2. (10 points) The Si bar shown is doped with 10^{17} phosphorous atoms per cm^3, and has donor mobility, $\mu_n = 700\ cm^2/Vs$. How much current will flow with the indicated applied voltage? [Hint: Conductivity, $\sigma = q\ \mu_n n_{o.}$]



The electric field (10V across 0.1 cm) is low enough to be in the ohmic region of conduction, so the given electron mobility, μ_n of roughly 700 $cm^2/V\text{-}cm$ should work fine.

$$\sigma = q\mu_n n_0 = 1.6 \times 10^{-19} \times 700 \times 10^{17} = 11.2(\Omega - cm)^{-1} = \frac{1}{\rho}$$

$$\rho = 0.0829\ \Omega \bullet cm$$

$$R = \frac{\rho L}{A} = \frac{0.08929 \times 0.1}{1 \times 10^{-6}} = 8{,}929\ \Omega$$

$$I = \frac{10 V}{8{,}929\ \Omega} = 1.12\ mA$$

3. An abrupt Si p-n junction has $N_a = 5x10^{16}\ cm^{-3}$ on the p side and N_d=$10^{17} cm^{-3}$ on the n side.

a. (10 points) Calculate the Fermi levels relative to E_{in} and E_{ip} and draw an equilibrium (no external bias) band diagram. Clearly indicate E_c, E_v, E_{in}, E_{ip} and E_F on your diagram.

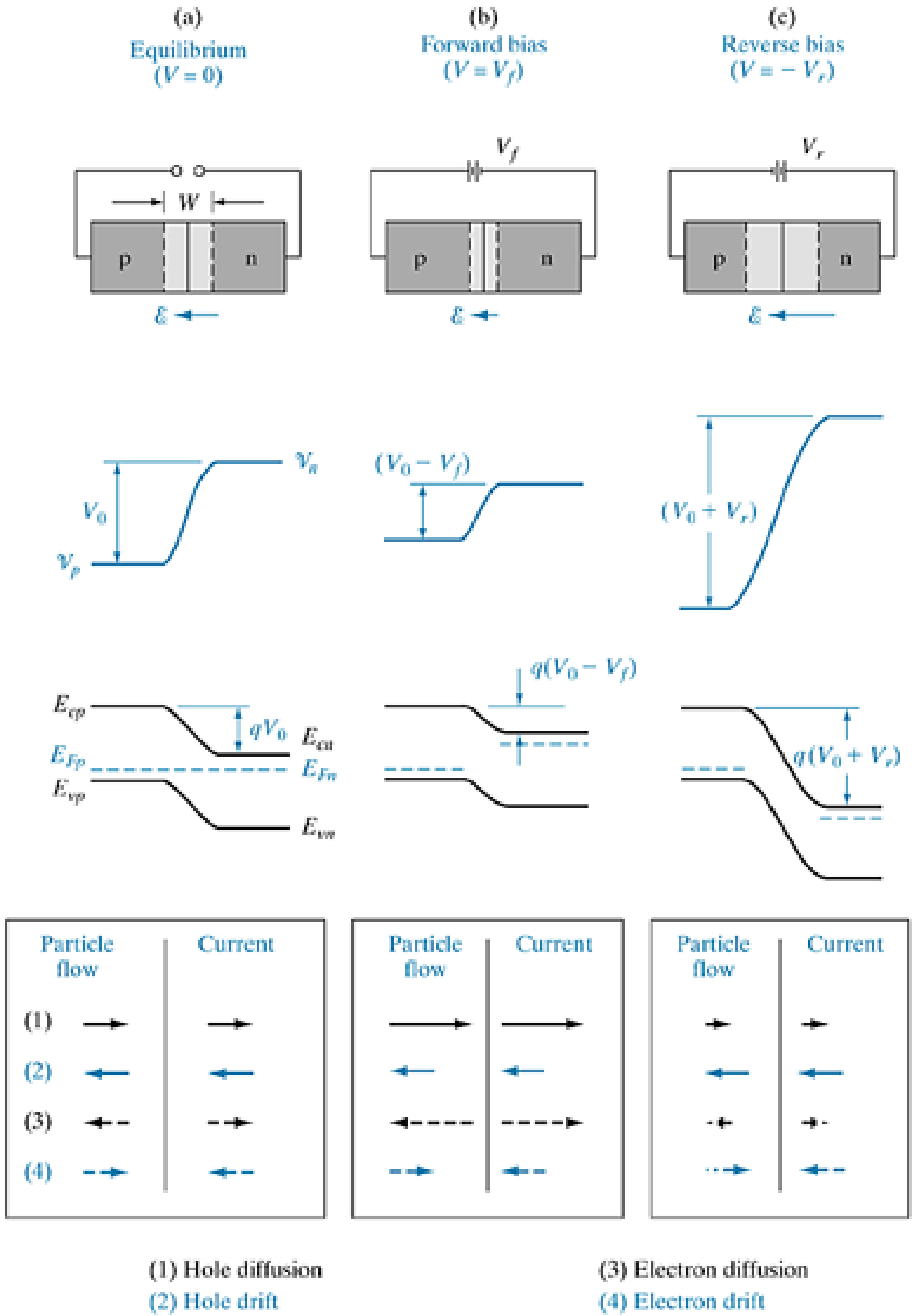
$E_{ip} - E_F = kT \ln (p_p/n_i) = 0.0259 \ln (5*10^{16}/1.5*10^{10}) = 0.389\ eV$
$E_F - E_{in} = kT \ln (n_n/n_i) = 0.0259 \ln (10^{17}/1.5*10^{10}) = 0.407\ eV$

b. (10 points) Calculate the contact potential and properly indicate it on the energy band diagram above.

$qV_0 = 0.389 + 0.407 = 0.796\ eV$
or
$qV_0 = kT \ln (N_a N_d/n_i^2) = .0259 \ln (5*10^{16}*10^{17})/(1.5*10^{10})^2$

$= 0.0259 \ln (2.22*10^{13}) = 0.796\ eV$

4. (10 points) The effect of forward and reverse bias on the energy band diagram and particle/current flow is basic to our understanding of p-n junctions. a) Draw the band diagram for cases (b) and (c) below. Make your drawing consistent with one given for equilibrium. b) Fill in the Particle flow/Current blocks for Forward and Reverse bias, using symbols consistent with the equilibrium case.



5. A silicon diode with a junction cross section of 10^{-4} cm^2 has the following characteristics:

p-side	*n*-side
$N_a = 7x10^{17}\ cm^{-3}$ $\tau_n = 0.1\ \mu s$ $\mu_p = 100\ cm^2/V\text{-}s$ $\mu_n = 400\ cm^2/V\text{-}s$	$N_d = 5x10^{16}\ cm^{-3}$ $\tau_p = 10\ \mu s$ $\mu_p = 400\ cm^2/V\text{-}s$ $\mu_n = 1350\ cm^2/V\text{-}s$

a) (15 points) Calculate V_0. Show your work and to indicate your answer clearly.

$$V_o = \frac{kT}{q}\ln\left[\frac{N_a N_d}{n_i^2}\right] \Rightarrow V_0 = 0.846\ V$$

b) (15 points) Calculate the junction width (W) at equilibrium. Show your work and indicate your answer clearly.

$$W = x_{n_0} + x_{p_0} = \left[\frac{2\varepsilon(V_0 - V)(N_a + N_d)}{qN_d N_a}\right]^{\frac{1}{2}}$$

$$\varepsilon = \varepsilon_r\varepsilon_0 = 11.8(8.85E-14)F/cm \Rightarrow W = 1.538\text{E-}5\ cm = 0.154\mu m$$

c) (15 points) Show calculations and clearly indicate reverse and forward currents (I_o and I) at applied voltages of $V = \pm 5V$.

REMEMBER: *Minority* carriers, use Einstein's equation to find the D's and L's and plug it in, ignoring Dr. Peeples stupid forward bias.

$$p_n = \frac{n_i^2}{n_n} = \frac{2.25x10^{20}}{5x10^{16}} = 4{,}500\ cm^{-3}$$

$$n_p = \frac{n_i^2}{p_p} = \frac{2.25x10^{20}}{7x10^{17}} 321.4 cm^{-3}$$

$$D_p = \frac{kT}{q}\mu_p = 0.0259\ x400 = 10.36\,cm^2/s$$

$$D_n = \frac{kT}{q}\mu_n = .0259\ x400 = 10.36\,cm^2/s$$

$$L_p = \sqrt{D_p\tau} = \sqrt{10.36\,x10\,x10^{-6}} = 1.02\,x10^{-2}\,cm$$

$$L_n = \sqrt{D_n\tau} = \sqrt{10.36\,x0.1x10^{-6}} = 1.02\,x10^{-3}\,cm$$

$$I_0 = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right) = 1.6x10^{-19}\,x10^{-4}\left(\frac{10.36}{1.02\,x10^{-2}}4500 + \frac{10.36}{1.02\,x10^{-3}}321.4\right) = 1.2536\ x10^{-16}\ A$$

$$I = I_0\left(e^{qV/kT} - 1\right) = 1.2536\ x10^{-16}\left(e^{5/.0259} - 1\right) = 8.69\,x10^{67}\ A$$

6. (5 points) Fill in the missing cells of the following table of Schottky Diode characteristics.

Material	*Relative Work Function*	*Nature of Interface*
p-Type	$\Phi_m > \Phi_s$	Ohmic
p-Type	$\Phi_m < \Phi_s$	Schottky Barrier
n-Type	$\Phi_m > \Phi_s$	Schottky Barrier
n-Type	$\Phi_m < \Phi_s$	Ohmic

(2 point each) Circle only one of the bold choices in each question below, or fill in the associated blank(s).

7. Majority carriers are depleted (due to diffusion) near the p-n junction. At equilibrium, this depleted region extends farther into the more **heavily-** or **lightly**-doped side of the junction.

8. Forward bias of a *p-n* junction **widens** or **narrows** the depleted region.

9. Junction capacitance **helps** or **hurts** switching speeds.

10. A junction formed by depositing a metal of proper work function directly on a semiconductor surface is called a ____Schottky Barrier___.

11. The two types of diode breakdown we studied are called ___Avalanche____ and ____Zener_________.