6.012 Fall 1998 - Answers to Exam #1

Problem 1

a) i) The dopant which is a donor has one more outer bonding electron than the atom it replaces in the lattice. Thus this donor, which replaces indium, must come from column IV.

ii) The sample is n-type so $n_o = N_D = 10^{17}$ cm^{-3}, and $p_o = n_i^2 / N_D = 10^{14}/10^{17} = 10^{-3}$ cm^{-3}. The fact that the later value is less than one is not "unphysical" because it is a density, not a number.

b) For time less than zero the excess concentration is $G\tau_{min}$, which is 10^{13} cm^{-3}. For t > 0 the concentration increases from this value to twice as much as $\exp(-t/\tau_{min})$:

$$n'(t) = G\tau_{min} + G\tau_{min}[1 - \exp(-t/\tau_{min})] = G\tau_{min}[2- \exp(-t/\tau_{min})] .$$

c) i) <u>Emitter-base junction</u>, because the peak electric field is proportional to the doping concentration on the more lightly doped side and thus the field is higher in the more heavily doped junction (i.e., the E-B junction), implying that the magnitude of the breakdown voltage will be lower in this junction because the breakdown field will be reached at a lower applied bias.

ii) <u>Collector-base junction</u>, because the saturation current is inversely proportional to the doping concentrations and thus is larger for the more lightly doped junction (i.e., the C-B junction).

iii) <u>Emitter-base junction</u>, because the capacitance is a measure of the inverse of the depletion region width. The depletion region width varies inversely with the doping levels and thus the inverse of the width varies directly as the doping levels, so does the capacitance, indicating that the larger capacitance is associated with the junction which has the larger doping levels (i.e., the E-B junction).

iv) <u>They will work but have a much smaller gain</u>, since we are now dealing with β_R, rather than β_F, or α_R, rather than α_F. Since $N_{DC} < N_{AB}$, the collector defect is large and α_R is much less than one, leading to a low β_R.

Problem 2

a) $\phi_b = (kT/q) \ln (N_{Ap}N_{Dn}/n_i^2) = 60 \log (10^{18}x10^{16}/10^{20}) = 60 \text{ x } 14 = 0.84$ V

b) $x_n/x_p = N_{Ap}/N_{Dn} = 10^{18}/10^{16} = 100$

c) We know that $p'(x_n) = p_{no} \exp (qv_{AB}/kT)$, and we want this to be $10^{-2}\, n_{no}$. Thus we can set these two equal and solve for v_{AB}, obtaining:

$$v_{AB} = (kT/q)\ln(10^{-2} n_{no}/p_{no}) = 60 \log(10^{-2} x 10^{16}/10^{4}) = 60 \text{ x } 10 = 0.6 \text{ V}$$

d) The problem statement tells us we are in a short base situation and that we can neglect the widths of the depletion regions so we know that the hole current density at x_n is $-qD_h\, dp'/dx\,|_{x_n}$ where dp'/dx is $-p'(x_n)/w_n$. $p'(x_n)$ is specified, D_h is $\mu_h/40 = 15\ cm^2/s$, and $w_n = 10^{-3}$ cm, so we know everything, and:

$$J_h(x_n) = 1.6 \text{ x } 10^{-19} \text{ x } 15 \text{ x } (10^{14}/10^{-3}) = 0.24\ A/cm^2$$

e) The ratio of the electron to hole current density is the emitter defect, or D_e/w_pN_{Ap} divided by D_h/w_nN_{Dn}, or $D_ew_nN_{Dn}/D_hw_pN_{Ap}$. Equivalently, we can write $\mu_ew_nN_{Dn}/\mu_hw_pN_{Ap}$., which we evaluate as:

$$1600 \text{ x } 10 \text{ x } 10^{16}/600 \text{ x } 5 \text{ x } 10^{18} = 5.33 \text{ x } 10^{-2}$$

f) i) The currents are constant throughout the device in a short-base situation so since it was specified that $J_e(-x_p)$ 0, we know that $J_e(x)$ 0, for all x, including $x_n < x < w_n$.

ii) We know the hole diffusion current for the region of interest, i.e. $x_n < x < w_n$, since $J_h(x_n)$ is specified to be 0.1 A/cm^2, and $J_h^{diff}(x)$ is the same as $J_h(x_n)$ for $x_n < x < w_n$. To get the electron diffusion current in this region we note that the electron diffusion current is $qD_e dn'/dx$, since dn'/dx dp'/dx, by quasineutrality, so we must have $J_e^{diff}(x) = -(D_e/D_h)\, J_h^{diff}(x)$, so

$$J_e^{diff}(x) = -(1600/600)\, 0.1 = -0.27\ A/cm^2$$

iii) The electric field can be found from a drift current and we know that since the total electron current is essentially zero, the electron drift current is the negative of the electron diffusion current:

$$J_e^{drift}(x) = q\,\mu_e\, n_{no}\, E(x) = -J_e^{diff}(x) = 0.27\ A/cm^2$$

Thus,

$$E(x) = 0.27/(1.6 \text{ x } 10^{-19} \text{ x } 1.6 \text{ x } 10^{3} \text{ x } 10^{16}) \quad 0.1\ V/cm$$

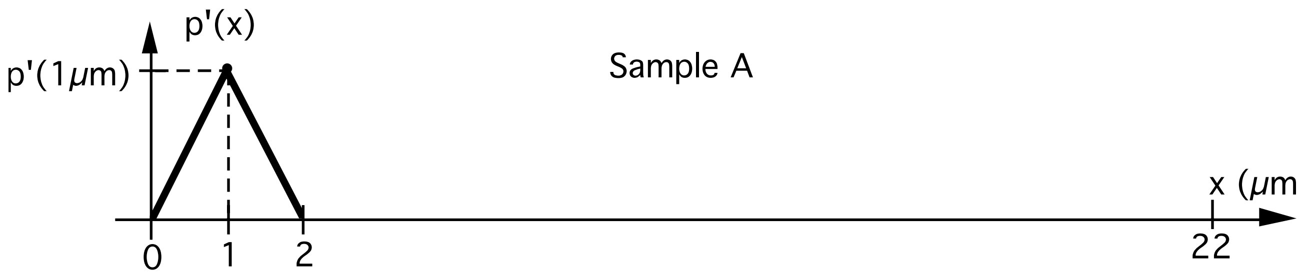
Problem 3

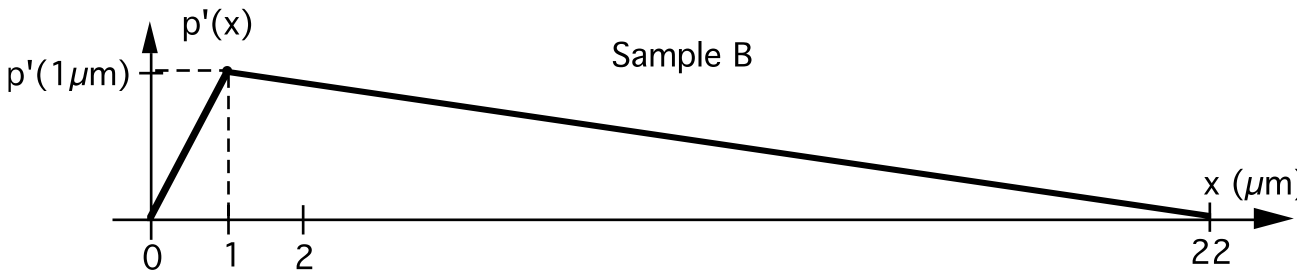
a) These are simple applications of standard relations. The Einstein relation gives us D_h and the definition of L_h gives us that:

$$D_h = \mu_h kT/q = 600/40 = 15\ cm^2/s$$

$$L_h = (D_h\tau_h) = (15 \text{ x } 10^{-6}) = 3.9 \text{ x } 10^{-3} \text{ cm} = 39\ \mu m$$

b) Since we are told to assume the minority carrier diffusion length is much greater than 22 µm, the profiles will be straight lines going from p'(1µm) to zero at the ohmic contacts:





c) i) The fluxes to each contact are proportional to the slopes of the profiles toward it. The slopes are equal in Sample A so equal amounts go to each contact and thus half goes to the contact at x = 0.

ii) In Sample B, the slope to the contact at x = 0 is 21 times greater than that to the contact at x = 22 so a fraction of 21/22 goes to x = 0, and 1/22 goes to x = 22.

d) Sample B, because....You either see this intuitively, or it takes a bit of work. Doing it quantitatively we add the diffusion fluxes and equate them to the optical input:

For Sample A: $D_h\, p_A' + D_h\, p_A' = M$, so $p_A' = M/2\,D_h$

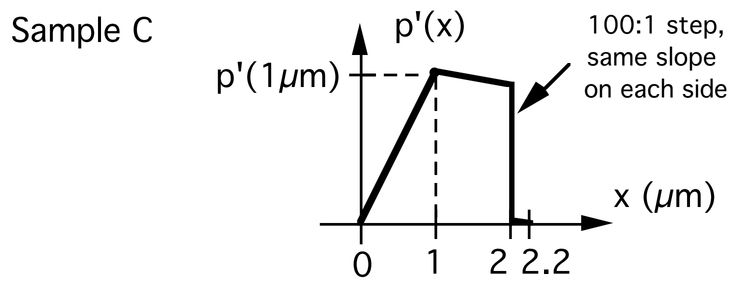
For Sample B: $D_h\, p_B' + D_h\, p_B'/21 = M$, so $p_B' = 21\,M/22\,D_h$

Comparing these two values, we see that $p_B' > p_A'$

e) $\phi_n = (kT/q)\ln(10^{16}/10^{10}) = 60 \log 10^6 = 60 \times 6 = 0.36$ V
$\phi_{n+} = = (kT/q)\ln(10^{18}/10^{10}) = 60 \log 10^8 = 60 \times 8 = 0.48$ V

f) The slope must be continuous across any boundary unless there is a source of hole-electron pairs, so $dp'/dx|_{x=2+} = dp'/dx|_{x=2-}$.

g) The profiles are straight lines going to zero at the ohmic contacts, with a 100:1 step and continuous slope at x = 2. The large step in concentration implies a large diffusion current of holes and electrons, but just as in a p-n junction, a dipole moment developes which creates equal and opposite drift currents so that the net additional current is zero ("additional" because there is already a minority carrier diffusion current, and majority carrier drift and diffusion currents crossing this boundary). The profile is:



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Exam 1 Statistics:

Average:	70.1
Standard Deviation:	15.5
Number taking exam:	57

Distribution: