ECE G201 Final Exam, April 17, 2009 Name_Brief solutions.
Include units on all numerical answers.

Problem 1 (33). A silicon pnp transistor has an emitter doped to $N_A = 5x10^{19}$ cm^{-3}, a base doped to $N_D = 7x10^{17}$ cm^{-3}, and a collector doped to $N_A = 10^{17}$ cm^{-3}.

a. (28) Taking into consideration the degenerate doping and bandgap narrowing of the emitter but not of the base, find β if the emitter is 0.1 μm thick (depletion layer to contact) and the base is also 0.1 μm thick (depletion layer edge to depletion layer edge, not metallurgical junction to metallurgical junction).
b. (5) Assuming that the position of the base-collector depletion layer edge given above corresponds to 2V of reverse bias, and the base-emitter junction is forward biased by 0.7 V, find the position of the actual base-collector metallurgical junction relative to the surface. A lot of work for 5 points, so you may want to do this last!

a. $\gamma \simeq \dfrac{1}{1+\frac{N'_{DB}}{N_V} e^{\Delta E_g/kT} \frac{D_{nE}}{D_{pB}} \frac{W_B}{W_E}} = \dfrac{1}{1+\frac{7\times10^{17}}{3.1\times10^{19}} e^{0.112/0.026} \frac{6.3}{8.4} \frac{0.1}{0.1}} =$

$N'_{DB} = 7\times10^{17}$ $W_B = 0.1\,\mu m$

$N_V = 3.1\times10^{19}$ $W_E = 0.1\,\mu m$

$\gamma = 0.443$

$\Delta E_g^* = 0.112\,eV$

$\beta = \dfrac{\gamma}{1-\gamma} = 0.795$

$D_{nE} = 6.3\ cm^2/s$

$D_{pB} = 8.4\ cm^2/s$

b. $w_n = \left[\dfrac{2\epsilon V_j}{qN'_D(1+N'_D/N'_A)}\right]^{1/2}$

$V_{bi} = \dfrac{kT}{q}\ln\left[\dfrac{N'_A N'_D}{n_i^2}\right]$

$= 0.026 \ln \dfrac{7\times10^{34}}{(1.08\times10^{10})^2} =$

$V_j = V_{bi} - V = V_{bi} + 2$

$V_j = 2.885V$

$V_{bi} = 0.885\ V$

$w_n = \left(\dfrac{2\times8.85\times10^{-14}\times2.885\times11.9}{(1.6\times10^{-19})(7\times10^{17})(1+\frac{7\times10^{17}}{10^{17}})}\right)^{1/2}$

$w_n = 2.60\times10^{-6}\,cm = 0.026\ \mu m$

metallurgical junction at depletion edge + 2.6 $\times10^{-2}$ μm

$p^+ - n$ junction: $qV_{bi} = \left[1.12 - kT \ln \frac{N_V}{N_A'}\right]$

$$= \left[1.12 - 0.026 \ln \frac{3.10 \times 10^{19}}{7 \times 10^{17}}\right]$$

$$= 1.02\ V$$

$p^+ - n$ $\quad w = \left[\frac{2 \epsilon V_i}{q N_D'}\right]^{1/2} = \left[\frac{2 \times 8.85 \times 10^{-14} \times 11.9\ (1.02 - 0.7)}{1.6 \times 10^{-19}\ \ 7 \times 10^{17}}\right]^{1/2}$

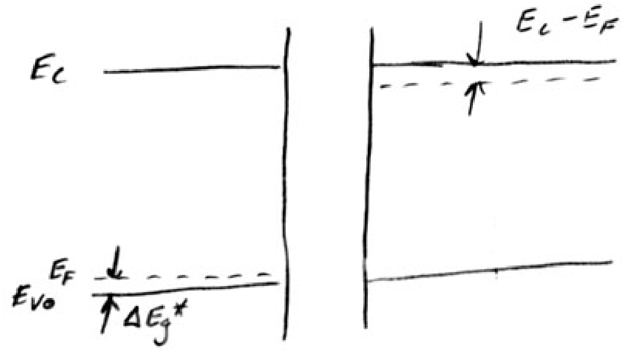
$$w = 2.45 \times 10^{-6}\ cm = 2.45 \times 10^{-2}\ \mu m$$

So metallurgical junction for B-C at $0.1 + 0.0245 + 0.1$

$+ 0.026\ \mu m = 2.51 \times 10^{-1} = 0.251\ \mu m$ below surface.

Problem 2. (25). For a PMOS transistor with equivalent gate oxide thickeness (t_0=1 nm, N_D=5e17, and a p^+ polysilicon gate doped at $7x10^{19}$):

a. Find the threshold voltage, assuming no fixed charge.
b. What implant dose (cm^{-2}) would be necessary to achieve a threshold voltage of -0.15V?
c. Would the implant consist of donors or acceptors, and what element would you pick?



ΔE_g^* @ $7 \times 10^{19} = 0.118\ eV$

$E_c - E_F = kT \ln \frac{N_c}{N_D} = 0.026 \ln \frac{2.86 \times 10^{19}}{5 \times 10^{17}} = 0.105\ eV$

$\Phi_{ms}/q = 1.12 - 0.118 - 0.105 = 0.897\ V$

$\Phi_f = E_i - E_F = kT \ln \frac{n_i}{N_D} = 0.026 \ln \frac{1.08 \times 10^{10}}{5 \times 10^{17}} =$

$\Phi_f = -4.59 \times 10^{-1} = -0.459\ V$

$C'_{ox} = \frac{3.9 \times 8.85 \times 10^{-14}}{10^{-7}} = 3.45 \times 10^{-6}\ F/cm^2$

$V_T = V_{FB} + 2\Phi_f - \frac{Q_B}{C_{ox}}$

$Q_B = \sqrt{2 \epsilon_s q N_D' 2\Phi_f} = 3.933 \times 10^{-7}$ (positive, donors)

$V_T = 0.897 - 0.918 - \frac{3.933 \times 10^{-7}}{3.45 \times 10^{-6}} = -0.135\ V$

b. $\Delta V = -0.015\ V = -\dfrac{Q_{Imp}}{C_{ox}}$

$$Q_{Imp} = (0.015)(C_{ox}) = (0.015)(3.45\times10^{-6}) = 5.175\times10^{-8}$$

$$\text{Dose} = \frac{Q_{Imp}}{q} = 3.23\times10^{11}\ cm^{-2}$$

c. Q_{imp} is + → Donor → As or P.

Problem 3. (25).

For the previous transistor, with a threshold of 0.2V, a low-field mobility of 200 $cm^2/V \cdot s$ (assume θ=0), and a saturation velocity of $4x10^6$ cm/s, with L=20 nm and W=400 nm:

a. what is I_D for V_{GS}=1V, V_{DS}=1V?
b. what is I_D for V_{GS}=1V, V_{DS}=0.1V?

$$V'_{Dsat} = \frac{V_{sat}}{\mu_{lf}} L \left[\left(1 + \frac{2\mu_{lf}(V_{GS}-V_T)}{V_{sat} L} \right)^{1/2} - 1 \right]$$

$V_{sat} = 4\times10^6$

$L = 20nm = 20\times10^{-7} cm$

$L = 2\times10^{-6} cm$

$\mu_{lf} = 200 \; cm^2/V \cdot s$

$$V'_{Dsat} = \frac{8}{200} \left[\left(1 + \frac{400(0.85)}{8} \right)^{1/2} - 1 \right]$$

$V_{GS} - V_T = 1 - 0.15 = 0.85V$

$V_{sat} L = 8$

$V'_{Dsat} \approx 0.224V$ @ $V_{GS} = 1V$

a. Saturation so

$$I_{Dsat} = \frac{W C'_{ox} \mu_{lf} \left(V_{GS} - V_T - \frac{V_{Dsat}}{2} \right) V_{Dsat}}{L \left(1 + \frac{\mu_{lf} V_{Dsat}}{L V_{sat}} \right)}$$

$$I_{Dsat} = \frac{20 \cdot 3.45\times10^{-6} \left(1 - 0.15 - \frac{0.224}{2} \right) 0.224 \; (200)}{\left(1 + \frac{200 \; (0.224)}{8} \right)}$$

$I_{Dsat} = 3.46 \times 10^{-4} A$

b. $V_{DS} < V_{Dsat}$ → not saturation

$$I_{D} = \frac{W C_{ox} \mu_{lf} \left(V_{GS} - V_T - \frac{V_{DS}}{2} \right)(V_{DS})}{L \left(1 + \frac{\mu_{lf} V_{DS}}{L V_{sat}} \right)}$$

$$I_D = \frac{20 \cdot 3.45\times10^{-6} \cdot 200 \; (1 - 0.15 - 0.05)(0.1)}{1 + \frac{200 \; (0.1)}{8}}$$

$I_D = 3.15 \times 10^{-4} A$ (Almost as large!)

Problem 3, 0.2V

$$V_{Dsat} = \frac{8}{200}\left[\left(1 + \frac{400(0.8)}{8}\right)^{1/2} - 1\right] = -0.216\ V$$

$$I_{Dsat} = -\frac{20 \cdot 3.45\times10^{-6}\left(1 - 0.2 - \frac{0.216}{2}\right)0.216\ (200)}{\left(1 + \frac{200(0.216)}{8}\right)}$$

$$I_{Dsat} = -3.22\times10^{-4}\ A$$

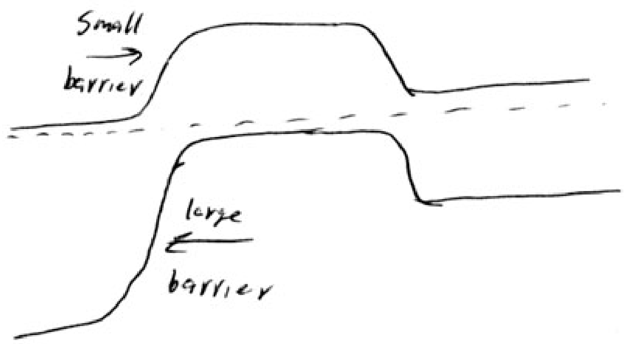
$$I_D\ @\ 0.1V = -\frac{20 \cdot 3.45\times10^{-4} \cdot 200(1 - 0.2 - 0.05)(0.1)}{1 + \frac{200(0.1)}{8}}$$

$$I_D = -2.96\times10^{-4}\ A$$

Problem 4. (17) Give short answers to the following:

a. How does a heterojunction to increase the β of a bipolar transistor. Explain using a band diagram.
b. Describe how using a HBT structure can permit the designer to increase the Early Voltage and the punchthrough voltage for a given transistor design.
c. Why do conventional p-n junction solar cells become less efficient as the bandgap increases?
d. Who do conventional p-n junction solar cells become less efficient as the bandgap decreases?
e. Explain why a double junction solar cell could be more efficient than a single junction solar cell.
f. Why does β decrease at low currents in a bipolar transistor? What is the physical mechanism that changes the ratio between the hole and electron currents?
g. What are the two effects that increase the apparent gate insulator thickness beyond the thickness of the insulator?

a Increase the bandgap of the emitter to decrease the injection of minority carriers



b. Because the "band gap barrier" is preventing injection of minority carriers into the emitter, the base no longer has to be lightly doped. This means that the depletion layer in the base can be small, and it is movement of this depletion layer that leads to the Early effect and punch through.

c. fewer photons are absorbed and fewer electron/hole pairs collected.

d. Less energy is obtained from each photon absorbed because V_{oc} is less.

e. One cell could absorb high energy photons efficiently and the second cou '' L_p collect lower energy photons for an increase L_n overall efficiency.

f. Recombination current increases relative to diffusion current. Recombination current injects no minority carriers, leading to no transistor action.

g. 1. Depletion layer in poly.

2. Location of channel electrons in quantum well - not right at surface.