Test 2 - EE 5340/4329 (print last name) Key (print first name)
Thursday, November 1, 2001, 9:30 AM
80 minutes allowed (last four digits of your student #) (e-mail if new)

Instructions:

1. Do your own work.
2. You may use either a legal copy of the text or one sheet of hand-written notes. You may NOT pass a book or note sheet to another student. You may NOT use class notes.
3. Calculator allowed. You may NOT share a calculator with another student.
4. Do not use previously solved problems.
5. Explicitly state definitions and assumptions that you use.
6. Where possible, calculate parameters rather than read them from a graph.
7. Do all work in the spaces provided on this exam paper. If you write on the back of a sheet, make the notation "PTO" in your solution in order to assure that material written on the back of the page is evaluated for a grade.
8. Show all calculations, making numerical substitutions and giving numerical results where possible.
9. Write answers in space given.
10. Unless stated otherwise, T = 300K, V_t = 25.852 mV
11. Unless otherwise stated, the material is silicon with n_i = 1.07E10 cm^{-3}, N_c = 2.84E19 cm^{-3}, N_v = 3.08E19 cm^{-3}, and $q\chi_s$ = 4.05 eV.
12. Use the relationship τ_{min} = [45E-6 sec]÷[1+7.7E-18*N_i+4.5E-36*N_i^2] (where N_i = the total impurity concentration) for minority carrier lifetime.
13. For holes assume μ_p = {418.3÷[1+(N_i÷1.6E17)$^{0.7}$]}+49.7, in cm^2/V-sec (where N_i = the total impurity concentration in n- or p-type material whether compensated or uncompensated).
14. For electrons assume μ_n = {1268÷[1+(N_i÷1.3E17)$^{0.91}$]}+92, in cm^2/V-sec (where N_i = the total impurity concentration in n- or p-type material whether compensated or uncompensated).
15. Each part is worth [x] points, as given in the problem.

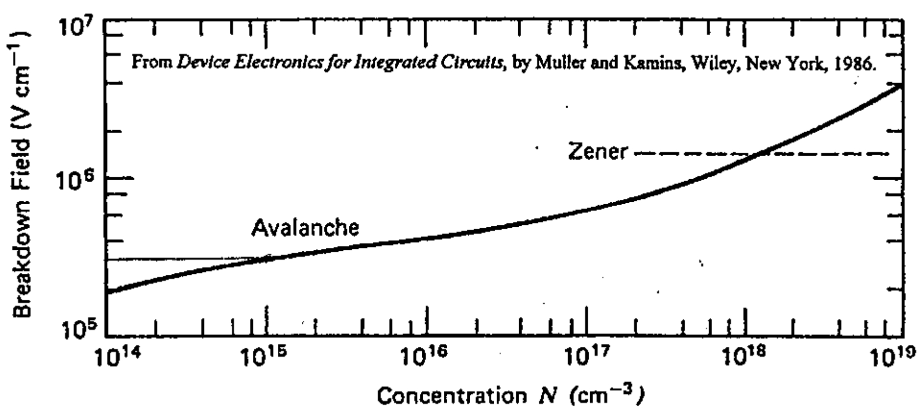

Figure 4.12 The critical electric fields for avalanche and Zener breakdown in silicon as functions of dopant concentration.[1,2,3]

1 A p^+n step junction diode has N_A=1E18/cm^3 on the p type side and N_D=1E15 /cm^3 on the n type side. The thickness of n type side is 3E-4 cm and the area is 800E-4 cm^2.

a Calculate the built-in potential.

$$V_{bi} = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.025852 \times \ln\left(\frac{1\times10^{18} \times 1\times10^{15}}{(1.07\times10^{10})^2}\right) = 0.77$$

a [6] Vbi = 0.77 V.

b Calculate the depletion width on the n type side when Va = 0V.

$N_A \gg N_D \quad N_{eff} = N^- = N_D$

$$x_n \approx W = \sqrt{\frac{2\varepsilon V_{bi}}{q N}} = \sqrt{\frac{2\times11.7\times8.85\times10^{-14}\times0.77}{1.6\times10^{-19}\times1\times10^{15}}} = 9.98\times10^{-5}\ \text{cm}$$

b [6] xn = 9.98×10^{-5} cm.

c Next, calculate the maximum electric field in the depletion region for Va = -10 V.

$$W(-10) = \sqrt{\frac{2\varepsilon(V_{bi}-V_a)}{q N^-}} = \sqrt{\frac{2\times11.7\times8.85\times10^{-14}\times10.77}{1.6\times10^{-19}\times1\times10^{15}}} = 3.73\times10^{-4}$$

$$E_{max} = \frac{2(V_{bi}-V_a)}{W(-10)} = \frac{2\times10.77}{3.73\times10^{-4}} = 5.77\times10^{4}\ \text{V/cm}$$

c [7] Emax = 5.77×10^{4} V/cm.

d Next, calculate the largest diffusion current term (either holes or electrons) for Va = 0.6V.

$$\tau_p = \frac{45\times10^{-6}}{1+(7.7\times10^{-18}\times1\times10^{15})+[45\times10^{-36}\times(1\times10^{15})^2]} = 4.47\times10^{-5}\ \text{s}$$

$L_p = \sqrt{D_p \tau_p} = 2.3\times10^{-2}$ $\quad W_n < L_p$ short

$$\mu_p = \frac{418.3}{1+\left(\frac{1\times10^{15}}{1.6\times10^{17}}\right)^{0.7}} + 49.7 = 456\ \text{cm}^2/\text{V.s}$$

$X_{n.CNR} = W_n - X_n \approx 2\times10^{-4}$ cm

$$D_p = \frac{KT}{q}\mu_p = 0.025852\times456 = 11.8\ \text{cm}^2/\text{s}$$

$$I_{diff} = A\cdot\frac{q D_p n_i^2}{X_{n.CNR}\cdot N_D}\times\exp\left(\frac{0.6}{V_t}\right)$$

$$= 800\times10^{-4}\times\frac{1.6\times10^{-19}\times11.8\times(1.07\times10^{10})^2}{2\times10^{-4}\times1\times10^{15}}\times\exp\left(\frac{0.6}{0.025852}\right)$$

$= 1.04$ A.

d [7] i_{diff} = 1.04 A.

e Next, calculate the breakdown voltage for this diode.

From the attached graph.

$N^- = 1\times10^{15}$ $\quad E_{crit} = 3.2\times10^{5}$

$$BV = \frac{\varepsilon E_{crit}^2}{2qN^-} = \frac{11.7\times8.85\times10^{-14}\times(3.2\times10^{5})^2}{2\times1.6\times10^{-19}\times1\times10^{15}} = 331$$

or. 5.16

$$BV = 60\left(\frac{E_g}{1.1}\right)^{3/2}\left(\frac{10^{16}}{10^{15}}\right)^{3/4} = 349$$

$E_g = 1.125$

e [6] BV = 349 V.

2 An ideal Au/p-Si Schottky- barrier diode with N_A = 1E16 cm^-3. ($q\phi_{Au}$ = 4.75eV)
a Calculate the barrier height.

(6.5) $q\Phi_{Bp} = q\chi + E_g - q\Phi_m = 4.05 + 1.125 - 4.75 = 0.425\ eV$.

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a [6] ϕ_{Bp} = 0.425 eV.
b Next, calculate the built-in potential.

$$V_{bi} = \frac{KT}{q}\ln\left(\frac{N_V}{N_A}\right) - \phi_{Bp} = 0.025852 \times \ln\left(\frac{3.08\times10^{19}}{1\times10^{16}}\right) - 0.425$$

$$= -0.217$$

b [6] Vbi = − 0.217 V.
c Next, calculate the depletion width when Va = 0V.

$$W = \sqrt{\frac{2\varepsilon V_{bi}}{q N_a}} = \sqrt{\frac{2\times11.7\times8.85\times10^{-14}\times0.217}{1.6\times10^{-19}\times1\times10^{16}}} = 1.68\times10^{-5}$$

c [6] W(Va=0) = 1.68×10^{-5} cm.
d Next, calculate the depletion capacitance per unit area when Va = -2V.

$$C = \sqrt{\frac{q\varepsilon N_a}{2(V_{bi}-V_a)}} = \sqrt{\frac{1.6\times10^{-19}\times11.7\times8.85\times10^{-14}\times1\times10^{16}}{2\times2.217}}$$

$$= 1.93\times10^{-8}$$

d [6] Cj'(Va=-2) = 1.93×10^{-8} Fd/cm^2

3 A gold gate ($q\phi_{Au} = 4.75$eV) to silicon MESFET is to be fabricated on an active layer with donor concentration Nd = 3E17 and thickness a = 1.5E-4 cm.

a Calculate the pinch-off voltage.

$$V_p = \frac{q N_d a^2}{2\varepsilon} = \frac{1.6\times10^{-19} \times 3\times10^{17} \times (1.5\times10^{-4})^2}{2\times 11.7\times 8.85\times10^{-14}} = 521.5$$

a [6] Vp = 521.5 V

b Calculate the threshold voltage.

$$V_{bi}^{n} = \phi_m - \chi_s - \frac{kT}{q}\ln\left(\frac{N_c}{N_D}\right) = 4.75 - 4.05 - 0.025852\times\ln\left(\frac{2.84\times10^{19}}{3\times10^{17}}\right)$$

$$= 0.523$$

$$V_T = V_{bi}^{n} - V_p = -521$$

b [6] V_T = −521 V

c Calculate the ratio $I_{D,sat}/(G_oV_p)$ at $V_{GS} = V_T + V_p$.

$$(6.70)\quad \frac{I_{Dsat}}{G_0 V_p} = \frac{1}{3}\left[1 - \frac{3(V_{bi}^{n} - V_{GS})}{V_p} + 2\left(\frac{V_{bi}^{n} - V_{GS}}{V_p}\right)^{3/2}\right] = \frac{1}{3}$$

$$V_{GS} = V_T + V_p = V_{bi}^{n}$$

c [7] $I_{D,sat}/(G_oV_p)$ = 0.333

4 An npn transistor has the following parameters at $V_{BE} = V_{BC} = 0$:
emitter charge neutral width = 10E-4 cm, N_{dE} = 5E18 cm^-3.
base charge neutral width = 0.85E-4 cm, N_{aB} = 5E16 cm^-3.
Collector charge neutral width = 10E-4 cm, N_{dC} = 2E16 cm^-3.

$N_B = 5\times10^{16}$. $W_B = 0.85\times10^{-4}$ cm

$N_E = 5\times10^{18}$. $W_E = 10\times10^{-4}$ cm

a. Calculate the emitter efficiency.

$$\mu_{PE} = \frac{418.3}{1+\left(\frac{5\times10^{18}}{1.6\times10^{17}}\right)^{0.7}} + 49.7 = 84.2$$

$$D_E = \frac{KT}{q}\mu_{PE} = 2.18$$

$$\mu_{nB} = \frac{1268}{1+\left(\frac{5\times10^{16}}{1.3\times10^{17}}\right)^{0.91}} + 92 = 986.$$

$$D_B = \frac{KT}{q}\mu_{nB} = 25.5$$

$$\tau_E = \frac{45\times10^{-6}}{1+(7.7\times10^{-18}\times5\times10^{18})+[4.5\times10^{-36}\times(5\times10^{18})^2]} = 2.96\times10^{-7}\ \text{s}$$

$$L_E = \sqrt{D_E\tau_E} = 8\times10^{-4} < W_E \Rightarrow \text{long}.$$

$$\gamma = \left[1+\frac{D_E N_B W_B}{D_B N_E L_{PE}}\right]^{-1}$$

$$= \left[1+\frac{2.18\times5\times10^{16}\times0.85\times10^{-4}}{25.5\times5\times10^{18}\times8\times10^{-4}}\right]^{-1}$$

$$= 0.9999$$

a [6] γ = 0.9999.

b Next, calculate the base transport factor.

$$L_B = \sqrt{D_B\tau_B} = \sqrt{25.5\times3.22\times10^{-5}} = 2.86\times10^{-2}\ \text{cm}$$

$$\tau_B = \frac{45\times10^{-6}}{1+(7.7\times10^{-18}\times5\times10^{16})+(4.5\times10^{-36}\times(5\times10^{16})^2)}$$

$$= 3.22\times10^{-5}$$

$$\alpha_T = 1-\frac{W_B^2}{2L_B^2} = 0.9999$$

b [6] α_T = 0.9999.

c Next, calculate the base transit time.

$$\tau_{tr} = \frac{W_B^2}{2D_B} = \frac{(0.85\times10^{-4})^2}{2\times25.5} = 1.42\times10^{-10}\ \text{s}$$

c [6] t_{Tr} = 1.42×10^{-10} s.

d Next, make a quick, but accurate as possible, estimate of the minority carrier current density at the base side of the emitter-base depletion region when V_{BE} is 0.6V and V_{BC} is 0V. Include a discussion as to how you would improve the accuracy.

$$J_{min,B}(x=0) = -q D_{min}\frac{\Delta P}{\Delta X}.$$

(when short) $\tau_{tr} < \tau_{min}$.

$$J_{nE}(0) = \frac{q D_{nB} n_i^2}{N_{aB} W_B}\exp\left(\frac{0.6}{0.025852}\right)$$

$$= \frac{1.6\times10^{-19}\times25.5\times(1.07\times10^{10})^2}{5\times10^{16}\times0.85\times10^{-4}}\exp\left(\frac{0.6}{0.025852}\right)$$

$$= 1.32\ \text{A/cm}^2$$

d [7] $J_{nE}(0)$ = 1.32 A/cm^2.