Test 2 - EE 5340/051 and EE 4329/001
November 3, 1998 (**PRINT** name)_____Key_____ (ssn)_____-___-____

Open book/handouts - no notes! Calculator allowed. ***If needed, you may refer to the handout for values of material constants.*** *Each part is worth [x] points. Explicitly state definitions and assumptions that you use. Show numerical substitution and calculate numerical results wherever possible. Be sure to show carefully how all answers are obtained. Unless otherwise noted, assume the material is silicon and that T = 300K. If only donor concentration is given, assume the acceptor concentration is zero. Likewise, if only acceptor concentration is given, assume the donor concentration is zero.* ***The time limit is 80 minutes.***

1a [9] A p+n diode has N_a = 5E18/cm^3 on the p+ side and N_d = 3E16/cm^3 on the n side. Calculate the current density, J_S, for V_a = 0.65 V. (You may assume $L_p << W_n$.)

Neglecting the electron flow contr. to the current and noting that D_p for N_d=3E16 is 10.06 cm^2/sec & τ_p=36.56 μs

$$L_p = \sqrt{D_p \tau_p} = 191.8\,\mu m$$

$$J_p = q n_i^2 \frac{D_p}{N_d L_p}\left(e^{V_a/V_t} - 1\right), \quad J_s = q n_i^2 \frac{D_p}{N_d L_p}$$

$$= 1.6E{-}19(1.45E10)^2 \frac{10.06}{3E16 * 1.92E{-}2}\left(e^{\frac{0.65}{0.02586}} - 1\right)$$

$$\boxed{J_p = 48.5\ mA/cm^2} \quad J_s = 5.88E{-}13$$

1b [8] At a current density of 100 mA/cm^2, the diode in **1a** (with an area of 1E-3 cm^2) has a resistance of 200 ohms. What is the diffusion capacitance?

$$r_d C_d = \tau = \tau_p$$

$$C_d = \tau_p / r_d$$

$$= \frac{36.56\,\mu sec}{200\ ohm}$$

$$\boxed{C_d = 182\ nFd}$$

Note: If calculate $r_d = \frac{0.02586\ V}{100 mA/cm^2 * 1E{-}3 cm^2}$ then r_d = 259 ohm & $C_d = \frac{36.56\mu}{259} = 141\ nFd$

1c [8] At V_a = 0.2 V, what is the recombination current density of the diode in **1a** (assuming τ_0 = 1E-7 sec)?

$$J_{rec} = \frac{q W n_i}{2\tau_0} e^{V_a/2V_t}$$

$$W = \sqrt{\frac{2\varepsilon\left(V_t \ln\left[\frac{5E18*3E16}{(1.45E10)^2}\right] - 0.2\right)}{1.6E{-}19 * 3E16}}$$

$$W = 1.72E{-}5\ cm, \quad V_{bi} = 0.884\ V$$

$$J_r = \frac{1.6E{-}19 * 1.72E{-}5 * 1.45E10}{2 * 1E{-}7} e^{\frac{0.2}{0.02586 \times 2}}$$

$$\boxed{J_r = 9.54E{-}6\ A/cm^2}$$

1d [8] What is the reverse generation current density of the diode in problem **1a** for V_a = -10 V? (Assume $\tau_0 = \tau_{gen}$.)

$$J_G = \frac{q n_i W}{2\tau_0}$$

$$W = \sqrt{\frac{2\varepsilon(0.884 - (-10))}{1.6E{-}19 * 3E16}}$$

$$W = 6.85E{-}5\ cm$$

$$J_g = \frac{1.6E{-}19 * 1.45E10 * 6.85E{-}5}{2 * 1E{-}7}$$

$$\boxed{J_g = 7.95E{-}7\ A/cm^2}$$

2a [8] A silicon wafer has N_d = 1E15/cm^3. Assuming an ideal metal-semiconductor interface, which metals listed on the last page of the handout will not make a Schottky diode?

$$\phi_s = \chi_s + V_t \ln \frac{N_c}{N_d}$$

$$= 4.05 + 0.02586 \ln\left(\frac{2.8E19}{1E15}\right)$$

$$\phi_s = 4.315$$

A Schottky diode is formed

if $\Phi_M > \phi_s = 4.315$, so for Ag (silver $\phi_M = 4.26$) and Al (aluminum, $\phi_M = 4.28$) a Schottky diode is not formed.

2b [9] What is the depletion width at V_a = -1.0 for a N_d = 1E17/cm^3 silicon to gold Schottky barrier diode?

$$V_{bi} = \phi_m - \phi_s =$$

$$= 5.1 - \left(4.05 + 0.02586 \ln \frac{2.8E19}{1E17}\right)$$

$$V_{bi} = 0.904 \text{ V}$$

$$W = \sqrt{\frac{2\varepsilon(V_{bi} - V_a)}{qN_d}}$$

$$= \sqrt{\frac{2*11.7*8.85E-14*(0.904-(-1))}{1.6E-19*1E17}}$$

$$\boxed{W = 0.157\,\mu m}$$

2c [8] Give at least two possible reasons that a capacitance measurement might not give a result consistent with the width calculated in **2b**.

The V_{bi} and/or W will be different for a real Schottky because

A. Barrier lowering
① - image effect
② - tunneling
③ B. Interface state pinning
④ C. Nd might not be constant

2d [8] What is the ideal forward Schottky diode current for a gold to n-silicon diode with A = 1E-4 cm^2 and V_a = 0.75 V (assume A* = 120 A/cm^2-K^2)?

$$\Phi_B = \Phi_M - \chi_s = 5.1 - 4.05 = 1.05V$$

$$I = I_s\left(e^{V/V_t} - 1\right)$$

$$I = A^* * 300^2 * e^{\frac{-1.05}{0.02586}}\left(e^{\frac{0.75}{0.02586}} - 1\right) * 1E-4$$

$$\boxed{I = 9.89 \text{ mA}}$$

Note: If $\chi_s = 4.01$, I = 2.1 mA

3a [9] An npn BJT has N_E = 8E18/cm^3, x'_E = 0.5E-4 cm, N_B = 5E16/cm^3, x_B = 1E-4 cm, and N_C = 1E15/cm^3 with x''_C = 5E-4 cm. (Notes: The values for x', x_B and x''_C correspond to $V_{BE} = V_{BC} = 0$. Assume all three regions are "short".) Calculate the emitter efficiency, γ.

Assume N_E is arsenic and that there is no compensation in base or emitter

$$J_{nE,s} = q n_i^2 \frac{D_B}{N_B x_B}, \quad J_{pE,s} = q n_i^2 \frac{D_E}{N_E x'_E}$$

$$\gamma = \frac{J_{nE}}{J_{nE}+J_{pE}} = \frac{1}{1+\frac{D_E N_B x_B}{D_B N_E x'_E}}$$

$$\gamma = \left(1+\frac{3.02*5E16*1E-4}{9.37*8E18*5E-5}\right)^{-1}$$

$$\boxed{\gamma = 0.99599}$$

3b [9] Calculate the current gain, β, for the device described in **3a**. Assume the recombination and generation currents are zero. ($J_R = J_G = 0$.)

$\beta = \frac{\alpha}{1-\alpha}$, $\alpha = \gamma\alpha_T\delta$, $\delta = 1$ since

$$\alpha_T \equiv \frac{1}{1+\frac{x_B^2}{2L_B^2}}, \quad L_B = \sqrt{D_B\tau_B}$$

$\tau_B = 3.249E-5$ sec, $L_B = 174\ \mu m$

$$\alpha_T = \left(1+\frac{1}{2*174^2}\right)^{-1}$$

$$\alpha_T = 0.99998$$

$$\boxed{\beta = \frac{\gamma\alpha_T}{1+\gamma\alpha_T} = 247}$$

3c [8] Calculate the voltage $V_{BE,H}$ at which the base region enters high level injection for the forward active region.

At high level injection (in base)

$$\delta n_p = n_{p0}\left(e^{\frac{V_{BE,H}}{V_t}}-1\right) = N_B$$

So $$V_{BE,H} = V_t \ln\frac{N_B^2}{n_i^2} = 2V_t \ln\frac{N_B}{n_i}$$

$$V_{BE,H} = 2*0.02586 \ln\left(\frac{5E16}{1.45E10}\right)$$

$$V_{BE,H} = 778.6\ mV$$

3d [8] Calculate the ratio I_C/I_B for the Ebers-Moll model (Equations 9.60 and 9.62 in the text) in the forward-active region.

$$I_C = \alpha_F I_{ES}\,\mathrm{expf}\left(\frac{V_{BE}}{V_t}\right) - I_{CS}\,\mathrm{expf}\frac{V_{BC}}{V_t}$$

note that $\mathrm{expf}(x) = e^x - 1$

$$I_B = -I_C - I_E = I_{ES}(1-\alpha_F)\,\mathrm{expf}\left(\frac{V_{BE}}{V_t}\right) + I_{CS}(1-\alpha_R)\,\mathrm{expf}\left(\frac{V_{BC}}{V_t}\right)$$

For F.A. $\mathrm{expf}\left(\frac{V_{BE}}{V_t}\right) = e^{V_{BE}/V_t} >> 1$

and $\mathrm{expf}\left(\frac{V_{BC}}{V_t}\right) = -1$, $V_{BC} << -V_t$

$$\frac{I_C}{I_B} = \frac{\alpha_F I_{ES}\exp\left(\frac{V_{BE}}{V_t}\right) + I_{CS}}{I_{ES}(1-\alpha_F)\exp\left(\frac{V_{BE}}{V_t}\right) - I_{CS}(1-\alpha_R)}$$

$$\boxed{\frac{I_C}{I_B} \to \frac{\alpha_F}{1-\alpha_F}, \text{F.A.}}$$