Project 2 Test - EE 5342 (print last name) ______________________ (print first name) ___Solution_______
9:30 AM, Tuesday April 14, 2005, 105 Nedderman Hall
80 minutes allowed (last four digits of your student #) ____________ (e-mail *if* new)______________________
Instructions: Seat Number ____________

1. Do your own work. DO NOT REMOVE THE STAPLE ON THIS EXAM.
2. You may use a legal copy of the text by Massobrio and Antognetti. You may write notes in your text. You may NOT pass a book or note sheet to another student, or class notes or previously solved problems. **You may use your Project 2 solution and must submit it with this test in your exam packet**.
3. Calculator allowed. You may NOT share a calculator with another student.
4. Where values or equations are given on this cover sheet, use them in lieu of any other source. If a value is not given, explicitly state definitions and assumptions that you use.
5. Where possible, calculate parameters rather than read them from a graph.
6. 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. AN EXTRA BLANK SHEET IS ATTACHED AT THE BACK OF THE EXAM.
7. Show all calculations, making numerical substitutions and giving numerical results where possible.
8. **The total for the test is 75. Up to 25 additional points will be given for the Project report**.
9. Unless stated otherwise,
   $T = 300K$, $V_t = 25.852$ mV
10. Unless otherwise stated, the material is silicon (300K) with
    $n_i = 1.45E10$ cm^{-3} $N_c = 2.8E19$ cm^{-3} $q\chi_{Si} = 4.05$ eV
    $E_{g,Si} = 1.124$ eV. $N_v = 1.04E19$ cm^{-3}
11. For the work function of poly silicon, use $\phi_{n+} = \chi_{si} = 4.05$ V
    $\phi_{p+} = \chi_{Si} + E_{g,Si}/q = 5.174$ V.
12. For minority carrier (either electrons or holes) lifetime in silicon, use the relationship
    $\tau_{min} = (4.5E\text{-}5 \text{ sec})/(1 + N_i/1E17 + (N_i/5E17)^2)$,
    where N_i = the total impurity concentration in cm^{-3}
13. For holes in silicon doped primarily with boron*, assume
    $\mu_p = \{470.5 \div [1+(N_i \div 2.23E17)^{0.719}]\}+44.9$, in cm^2/V-sec.
14. For electrons in silicon doped primarily with phosphorous*, assume
    $\mu_n = \{1414 \div [1+(N_i \div 9.2E16)^{0.711}]\}+68.5$, in cm^2/V-sec.
15. For electrons in silicon doped primarily with arsenic, assume
    $\mu_n = \{1417 \div [1+(N_i \div 9.68E16)^{0.68}]\}+52.2$, in cm^2/V-sec.
    (In 12 through 15, N_i = the total impurity concentration in n- or p-type material, compensated or not.)
    (*13 may be used as an approximation for holes as minority carriers, likewise *14 for minority electrons.)
16. Metal gate work functions should be assumed to be
    $\phi_{M,Al} = 4.1$ V for aluminum, $\phi_{M,Pt} = 5.3$ V for platinum, $\phi_{M,Au} = 4.75$ V for gold
17. The electron affinity of SiO_2 is $\chi_{SiO2} = 1.00$ V.
18. Planck constant $h = 6.625E\text{-}34$ J-s = 4.135E-15 eV-s, (1 eV = 1.602E-19 Joule).
19. free electron mass $m_o = 9.11E\text{-}28$ g.
20. Boltzmann constant, $k = 1.38066E\text{-}23$ J/K
21. Electron charge, $q = 1.60218E\text{-}19$ Coulomb
22. Permittivity of free space, $\varepsilon_o = 8.854E\text{-}14$ Fd/cm
23. Relative permittivity of silicon, $\varepsilon_r = 11.7$
24. Relative permittivity of silicon dioxide, $\varepsilon_{rOx} = 3.9$
25. The breakdown voltage of an abrupt (step) junction (asymmetrical or one-sided) diode with doping on the lightly doped side of N_B is $V_B = 60(Eg/1.1)^{3/2}(10^{16}/N_B)^{3/4}$ V. The critical field for breakdown is modeled as $E_{crit} = (120V \cdot qN_B/(\varepsilon_r\varepsilon_0))^{1/2} \cdot (Eg/1.1)^{3/4} \cdot (10^{16}/N_B)^{3/8}$
26. Each part is worth [x] points, as given in the problem.

Note: Throughout the exam, $\ln(x) = \log_e(x)$, and $\log(x) = \log_{10}(x)$. Unless otherwise given or implied, assume V_t is as given in note 9 on the cover page.

1. [5] A SPICE simulation is done on a diode with IS = 2E-14 A, N = 1.1 and RS = 1. For the range of 700 mV to 1000 mV, a plot of log(I) *vs.* V has a constant slope of 0.015250 decade per mV. What value of V_t is this version of SPICE assuming?

This means 0.015250 = d(log(i))/dv = [d(ln(i))/dv]/2.302585093

➔ dv/d(ln(i)) = (0.015250*2.30258)^-1 = 28.478 mV = Vt for the simulation

2. This part refers to data taken for a forward gummel setup ($v_{CBext} = 0$, 350 mV < v_{BEext} < 950 mV).

a. [5] Give reasons that $dv_{BEext}/d(\ln(i_C))$ may have a value that is not exactly constant for the entire range of 350 mV < v_{BEext} < 450 mV.

1. The effect of the qB term – both VAR (especially for low vBE values) and IKF factors (for high vBE values)
2. The effect of RBB and RE for high vBE values.

b. [5] How is the best estimate for NF calculated from $dv_{BEext}/d(\ln(i_C))$?

NFextracted = minimum value of dvBEext/d(ln(iC))/Vt, where Vt should be the value the SPICE version uses for the temperature at which the measurements are taken.

c. [5] Since $dv_{BEext}/d(\ln(i_C))$ is not constant, which value should be used to estimate NF – the maximum, minimum or average value? Why?

See the answer to 2b.

3. a. [5] Describe two methods that can be used to extract a value for BF.

3a1. Use the maximum value of ic/ib

3a2. Use the maximum value of dic/dib

3a3. Use the maximum value of ic/(ib-ILE), where ILE is computed from ISE*exp(vbe/NE*VT)

b. [5] Using the Gummel Poon equations, make an argument for which of the two methods in part 3a should be more accurate. Should one expect the extracted value to be greater than or less than the best experimentally determined value for BF?

3a3 will be the most accurate as the other methods underestimate BF by overestimating the IBF by approximating it by ib ~ IBF + ILE.

4. a. [5] Describe two methods that can be used to extract values for RE and RB from forward Gummel data.

4a1. One can use the refly method of leaving C open-circuited and letting RBB ~ (vB-vC)/ib

and RE ~ (vC-vE)/ib.
4A2. Taking the derivative of diB/diB = 1, one finds that diB/dvBE – NF*Vt/iB ≡ rpi,adj = RE*diC/diB + (RB+RE). Such a plot of rpi,adj vs. hfe ≡ diC/diB gives a slope = REextr, and an intercept = RBextr.

b. [5] Using the Gummel Poon equations, make an argument for which of the two methods in part 4a should be more accurate.

One can show that vC when iC = 0 is not the potential of either the internal base node nor of the internal emitter node, so the equations in 4a1 are only approximate. The method in 4a2 is in error only because ib = IBF + ILE. If IBF >> ILE, it is relatively accurate.

5. [5] How would you extract a value for IKF? Support your assertion by reference to the Gummel Poon equations.

5a. Use the value of ic when ic/ib = $\frac{1}{2}$ $(ic/ib)_{max}$
5b. Use the value of ic when dic/dib = $\frac{1}{2}$ $(dic/dib)_{max}$
5c. Use the of ic when ic/(ib-ILE) = $\frac{1}{2}$ $(ic/(ib-ILE))_{max}$, where ILE is computed from ISE*exp(vbe/NE*VT). This is the best way. Putting this into the GP equations gives IKF

6. a. [5] How would one extract values for ISE and NE?

Use the low voltage ib data. Look for the maximum stable value observed for (dvBE/diB)/Vt ~ NE. Evaluation of ISEeff = exp[ln(i) – vBE/(Neff*Vt)] at the same vBE as NE was determined.

b. [5] With the data given for the project, would you expect that the value of NE is high or low? Why?

Since NE never reaches a stable or constant value and is increasing with decreasing value of vBE, one would assume NEextr is < NE.

c. [5] With the data given for the project, would you expect that the value of ISE is high or low? Why?

Since NE is low, the equation in part 6 suggests ISE is low.

7. [5] How would you estimate the forward Gummel voltage at which the currents IBF and ILE are equal?

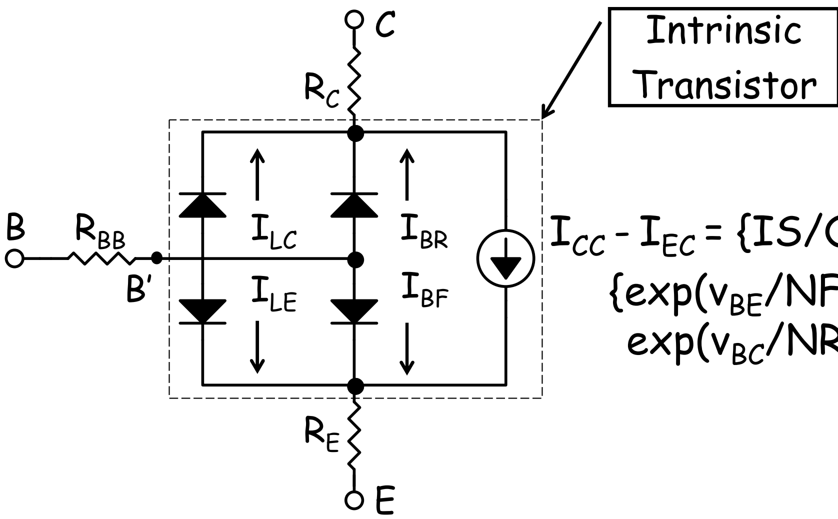
Plot the extracted value of set IBF = (IS/BF)*exp(vBE/NF*Vt) = ILE = ISE*exp(vBE/NE*Vt) and solve for vBE.

8. a. [5] In the reverse Gummel data for the project, it did not appear that the current ILC was significant. Note, however that $dv_{BCext}/d(\ln(i_E)) \neq dv_{BCext}/d(\ln(i_B))$. Is this possible, if ILC = 0 (you may assume that the value of VAR is not significant in explaining this).

If ILC << IBR, then data for much lower vBE must be used to extract the data. In this case, the extraction was made difficult by the data being generated with NR = 1.00 and NC = 1.11. So as consequence, [dvBCext/d(ln(iE))]/Vt = 1.00 by extraction and, [dvBCext/d(ln(iB))]/vT = 1.104. One must assume that the 1.104 value is dvBCext/d(ln[IBR+ ILC]). Since one already knows IS and BR, one can estimate ILB by calculating ILCex = iB – IS*exp(vBC/[NR*Vt]), when this is done, calculate [dvBCext/d(ln[ILCex])]/Vt = NCex, and
ISCextr = exp[ln(ILCex) – vBC/(NCex*Vt)].

b. [5] If $dv_{BCext}/d(\ln(i_E)) = 1$ and $dv_{BCext}/d(\ln(i_B)) = 1.1$, and assuming BR = 2, how would you estimate NC and ISC even if $dv_{BCext}/d(\ln(i_B)) = 1.1$ for a wide range of v_{BCext} values?

See 8b.



$$I_{CC} - I_{EC} = \{IS/Q_B\}^* \{\exp(v_{BE}/NFV_t) - \exp(v_{BC}/NRV_t)\}$$

$$I_{BF} = IS \;\; \mathrm{expf}(v_{BE}/NFV_t)/BF$$

$$I_{LE} = ISE \;\; \mathrm{expf}(v_{BE}/NEV_t)$$

$$I_{BR} = IS \;\; \mathrm{expf}(v_{BC}/NRV_t)/BR$$

$$I_{LC} = ISC \;\; \mathrm{expf}(v_{BC}/NCV_t)$$

$$I_{CC} - I_{EC} = IS(\exp(v_{BE}/NFV_t - \exp(v_{BC}/NRV_t)/Q_B$$

$$Q_B = \{\tfrac{1}{2} + [\tfrac{1}{4} + (BF\ IBF/IKF + BR\ IBR/IKR)]^{1/2}\} *(1 - v_{BC}/VAF - v_{BE}/VAR)^{-1}$$

In this case, the voltage across the diodes,

$v_{BE} = v_{BEx} - i_B*(RBB+RE) - i_C*RE$, etc.