Project 1 Test - EE 5342 (print last name) ______________________ (print first name) __Solution__________
9:30 AM, Thursday March 24, 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 1 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 = 25.843 mV (to agree with M&K k and q values)
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
    τ_{min} = (4.5E-5 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
    μ_p = {470.5÷[1+$(N_i$÷$2.23E17)^{0.719}$]}+44.9, in cm^2/V-sec.
14. For electrons in silicon doped primarily with phosphorous*, assume
    μ_n = {1414÷[1+$(N_i$÷$9.2E16)^{0.711}$]}+68.5, in cm^2/V-sec.
15. For electrons in silicon doped primarily with arsenic, assume
    μ_n = {1417÷[1+$(N_i$÷$9.68E16)^{0.68}$]}+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 χ_{SiO2} = 1.00 V.
18. Planck constant h = 6.625E-34 J-s = 4.135E-15 eV-s, (1 eV = 1.602E-19 Joule).
19. free electron mass m_o = 9.11E-28 g.
20. Boltzmann constant, k = 1.38E-23 J/K
21. Electron charge, q = 1.602E-19 Coulomb
22. Permittivity of free space, ε_o = 8.854E-14 Fd/cm
23. Relative permittivity of silicon, ε_r = 11.7
24. Relative permittivity of silicon dioxide, ε_{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 that throughout this exam:

1. va = Va represents the voltage across the diode depletion region,
2. vext = Vext represents the external applied voltage, and
3. the device area is assumed to be 804 μm^2 (1 μm = 1E-4cm = 1×10^{-4} cm).
4. The SPICE model for the junction capacitance is $C_j = CJ0\{1 - V_a/VJ\}^{-M}$, where V_a is the voltage across the depletion region and CJ0, VJ and M are SPICE parameters. .

1a. [4] For this project, what range of Vext values are best used when applying the definition of the parameter $y \equiv \{d[\ln(C_j)]/dV\}^{-1}$, and dy/dV to determine VJ and M? Which ranges for the data given below will fit the SPICE model best?
(a) -4 V < Vext < 0.5 V
(b) -0.5 V < Vext < 0.5 V
(c) 0 V < Vext < 0.5 V

The best range is (c). In the case of the solution, the data for 100 mV < V < 500 mV were used. (Remember central derivatives were used.)

1b. [4] Support your argument (for a, b, or c above) based on the plot of y *vs.* Vext given in your report.

In the case of Figure A3.1, a value of R^2 closer to 1 would have been obtained if only the three points at highest V values were used. (This is due to the curvature of the plot.) Note that this essentially means the SPICE C-V model is not appropriate for V < 0.1 V.

1c. [4] Relate this to possible physical effects in the device.

This is probably due to the nature of the PiN type diode structure. Effectively, the diode looks like a true Pn diode only for voltages above the punch through voltage (which in the case of this structure is about 0 V). Below that voltage, the diode looks like a SPICE model in parallel with a constant capacitance, Ci = ε A/Wi, where Wi is the intrinsic region width and A is the diode area.

1d. [5] It was pointed out in one of the demonstrations in 212 ELB that placing a constant capacitance Ci in parallel with Cj and Cd could help fit the Cj model to the data better. (Ci is interpreted as the total capacitance of the diode when the depletion region reaches exactly across the intrinsic – lightly doped – region of the device.) Comment on the effectiveness of this approach in the range -4V < Vext < -1V (range 1a above). In this case, then the junction capacitance would be modeled by $Ci + CJ0\{1 - V_a/VJ\}^{-M}$. Where the zero voltage capacitance Cj(Vext = 0) = CJ0 + Ci.

See above. The SPICE model doesn't work for lower (and reverse) biases. The observations are that for approximately -4 V < V < -0.5 V, the capacitance is constant. The parallel combination will give this type characteristic, as the SPICE model capacitance << Ci as defined above for this voltage range.

1e. [4] What value of intrinsic region thickness does this capacitance infer?

See part C2 of the project solution.

1f. Discuss how consistent the result in 1e for Wi is with the N(x) profile you determined?

This is answered in C1 and C2 of the project solution.

2a. [4] What Vext value did you use to extract IS and N using the extraction procedure based on iseff and neff for fitting the SPICE model to the 700 mV < Vext < 1000 mV data?

See D1.

2b. [5] Based on the graph of iseff and neff *vs.* Vext, why is that (answer 2a) the best Vext to use for extraction?

This is where an extremum (minimum in neff and ISeff) occur.

2c. [4] Comment on the effect of using larger or smaller values of Vext.

In either case, neff and IS will increase, giving a steeper log(i) vs V model. The slope of the model is already close to correct, so this is the best value if N. The value of I for the model is too high, so a small degrease in IS will improve the model.

2d. [5] Comment on improvements you might expect using the procedure of extrapolation to large currents by plotting iseff and neff as a function of 1/ia for determining IS and N from ia *vs.* Vext data.

This will only lead to larger N values in the model, so will not help. This technique usually works for RS.

2e. [5] Discuss how you would determine IS, N, ISR, NR from neff and iseff using Va ~ Vext – Id*RS (assuming you have some *a priori* knowledge of RS).

One way would be to do all derivatives in terms of V' = V – Id*Rs. In this case, the high voltage limit for neff and ISeff are probably better estimated of N and IS. In other words, if a good knowledge of RS is obtained (as in the Z-parameter data), then the minimum in neff and ISeff are usually at the highest voltage.

2f. [4] Comment on which value of Vext you used to extract ISR and NR to fit the data in the 700mV < vext < 1000mV range and how that was changed when you extracted ISR and NR to fit the data in the 300mV < vext < 1000mV range.

Once again, the extremum (in this case a maximum for the 300 mV data) was used. The interesting result was that the extraction for 300 mV data actually gave a better 700 mV fit also.

3a. [5] Compare the TT value you obtained from the y-parameter data to the minority carrier lifetime in the intrinsic region (remember this is a PnN diode, so the minority carriers in the intrinsic region are holes) and to the minority carrier transit time in the intrinsic region. Use the intrinsic region width you got from C-V data in the -4V < Vext < -1V region and the intrinsic region majority carrier concentration you got for N(x) in the same voltage range.

In this case, the 500 nsec > TT > 10 nsec. Using Ni ~ 1E16/cm3 and Wi ~ 0.44 micron,

$$\tau_{min} = (4.5E\text{-}5\ sec)/(1 + Ni/1E17 + (Ni/5E17)^2) = 40.9\ \mu sec$$

$$\tau_{TR} = \frac{W_i^2}{2D_{min}} = \frac{W_i^2}{2D_{min}V_t} = (0.44E-4cm)^2 \Big/ \left(2\left(\frac{1414}{1+\left(\frac{Ni}{9.2E16}\right)^{0.711}} + 68.5\right)0.02582\right) = 30\ psec,$$

So the minority carrier lifetime is too short, and the transit time is too long. This diode comes into one of the in-between cases – neither short nor long.

3b. [4] Consider the y-parameter data given below. Calculate the Re{Z} and infer the value of RS from Re{Z} data at high frequency. Note: at high frequencies, Cj + Cd short circuits the diode conductance, so the only circuit element left in the diode model is RS. Solve symbolically for Re{Z} in terms of Re{Y} and Im{Y}.

The Re{Z} = Re{Y}/[(Re{Y})^2 + (Im{Y})^2]. These are the same data as in the project. So

va	ia	Re{Z},10G
0.30	2.79E-10	0.00
0.50	2.45E-08	4.83
0.70	3.26E-06	7.14
0.80	4.18E-05	4.76
0.90	1.01E-03	2.89
1.00	1.34E-02	2.45

Are the values to be filled in below

3c. [6] Fill in the values for Re{Z} in the table below.

frequency	300 mV, ia = 27.9 pA			500 mV, ia = 24.5 nA			700 mV, ia = 3.25 micro A		
	Re{Y}	Im{Y}	Re{Z}	Re{Y}	Im{Y}	Re{Z}	Re{Y}	Im{Y}	Re{Z}
4.00E+09	2.18E-04	6.70E-03		8.96E-04	1.10E-02		1.32E-01	9.91E-02	
8.00E+09	8.64E-04	1.33E-02		3.36E-03	2.13E-02		1.79E-01	7.32E-02	
1.00E+10	1.34E-03	1.66E-02		5.04E-03	2.61E-02		1.88E-01	6.45E-02	

frequency	800 mV, ia = 41.8 micro A			900 mV, ia = 1.01 mA			1000 mV, ia = 13.4 mA		
	Re{Y}	Im{Y}	Re{Z}	Re{Y}	Im{Y}	Re{Z}	Re{Y}	Im{Y}	Re{Z}
4.00E+09	3.35E-01	5.40E-02		4.07E-01	9.61E-03		4.25E-01	2.02E-03	
8.00E+09	3.43E-01	3.03E-02		4.08E-01	5.41E-03		4.25E-01	1.17E-03	
1.00E+10	3.44E-01	2.56E-02		4.08E-01	4.55E-03		4.25E-01	9.79E-04	

3d. [4] What function does RS(ia) seem to fit from the above data (i.e., a linear function of ia, linear plus constant, log, log plus constant, etc.)?

This is a function that first increases and then decreases. One try would be a parabola (2nd order polynomial).

3e. [4] Comment on which value of RS is the best choice for extraction: From dVext/dIa, Vext/Ia, or using the limit of Re{Z} at high current. If a single value is to be used, the value corresponding to the highest current. This agrees with the dc extraction. The best would be to introduce a current dependent resistor model for RS.