MidTerm - EE 5342 (print last name) ___Key___ (print first name) ____________
9:30 AM, Thursday February 12, 2004, 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. You may NOT use class notes or previously solved problems.
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. Write answers in space given.
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
    $\tau_{min} = (4.5E\text{-}5\ sec)/(1 + N_i/1E17 + (N_i/5E17)^2)$,
    where N_i = the total impurity concentration in cm^{-3}
13. For holes in silicon doped primarily with boron*, assume
    $\mu_p = \{470.5 \div [1+(N_i \div 2.23E17)^{0.719}]\}+44.9$, 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, $k = 1.38E\text{-}23$ J/K
21. Electron charge, $q = 1.602E\text{-}19$ 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.

Be sure to note the special conditions for statements 12 through 15 after statement 15 on page 1.

1 A region of silicon has 3E15/cm^3 phosphorous and 5E16/cm^3 boron.

a Calculate the majority carrier concentration and type.

$N = N_d - N_a = 3E15 - 5E16 = -4.7E16 < 0$

$\Rightarrow$ p type material, majority carrier is hole

$p = 4.7\times10^{16}/cm^3$

Answer 1a[7] Majority carrier concentration = 4.7×10^{16} /cm^3, type = hole (p) .

b Calculate the minority carrier concentration and type.

$n = \frac{n_i^2}{p} = \frac{(1.45\times10^{10})^2}{4.7\times10^{16}} = 4.473\times10^3/cm^3$

Answer 1b[7] Minority carrier concentration = 4.473×10^3 /cm^3, type = electron (n)

c Calculate the majority carrier mobility.

$\mu_p = \frac{470.5}{1+(N_i/2.23E17)^{0.719}} + 44.9$ where $N_i = N_{phos} + N_{boron} = 5.3E16$

$= 391.9\ cm^2/V\cdot sec$

Answer 1c[6] Majority carrier mobility = 391.9 cm^2/V-sec.

d Calculate the minority carrier diffusion coefficient.

$\mu_n = \frac{1414}{1+(\frac{N_i}{9.2E16})^{0.711}} + 68.5 = 912.4\ cm^2/V\cdot sec$

$D_n = \mu_n V_T = \mu_n \cdot 0.025843 = 23.58\ cm^2/sec$

Answer 1d[6] Minority carrier diffusion coefficient = 23.58 cm^2/sec.

e This material is made into a diode with the doping on the other side being 3E15/cm^3 phosphorous. What is the contact potential of this diode?

$V_{bi} = \phi_i = V_t \ln\left[\frac{4.7E16 \times 3E15}{(1.45E10)^2}\right] = 0.704\ V$

Answer 1e[6] Contact potential = 0.704 V.

f What is the capacitance per unit area for this diode when the applied voltage is zero volts?

$C_J(0) = \sqrt{\frac{8\varepsilon_0\varepsilon_r N'}{2\phi_i}}$ where $N' = \frac{N_A N_D}{N_A+N_D} = \frac{3E15\times4.7E16}{3E15+4.7E16} = 2.82E15$

$\Rightarrow \sqrt{\frac{1.602\times10^{-19}\times8.854\times10^{-14}\times11.7\times2.82E15}{2\times0.704}} = 1.823\times10^{-8}\ Fd/cm^2$

Answer 1f[6] Capacitance per unit area = 1.823×10^{-8} Fd/cm.^{2}

2 A region of silicon has p = 1E17/cm^3 and a majority carrier mobility of 300 cm^2/V-sec, and a minority carrier mobility of 700 cm^2/V-sec. Assume that the total impurity concentration is 1.5E17/cm^3.

a What is the minority carrier lifetime in this region?

$$\tau_{min} = \frac{4.5\times10^{-5}}{1+\frac{N_i}{10^{17}}+\left(\frac{N_i}{5\times10^{17}}\right)^2} \quad \text{where } N_i = 1.5E17$$

$$\Rightarrow \frac{4.5\times10^{-5}}{1+1.5+\left(\frac{1.5}{5}\right)^2} = 1.74\times10^{-5} \text{ sec}$$

Answer 2a[6] The minority carrier lifetime is 1.74×10^{-5} sec.

b What is the minority carrier diffusion length in this region?

minority carrier is electron.

$\mu_n = 700$ cm^2/V-sec

$\Rightarrow L = \sqrt{D_n \tau_{min}} = \sqrt{18.09\times1.74\times10^{-5}}$

$= 1.774\times10^{-2}$ cm

$\therefore D_n = \mu_n V_T = 700 \times 0.025843 = 18.09$ cm^2/sec

Answer 2b[6] The minority carrier diffusion length is 1.774×10^{-2} cm.

c What is the saturation current density for minority current injection into this region from an n+ cathode region into the anode region described above (assuming a long diode)?

$$J = q n_i^2 \frac{D_n}{N_{A,eff} L_{min}} = 1.602\times10^{-19}\times(1.45\times10^{10})^2 \frac{18.09}{10^{17}\times1.774\times10^{-2}} = 3.43\times10^{-13} \text{ A/cm}^2$$

Answer 2c[6] The saturation current density is 3.43×10^{-13} A/cm2.

d What is the long diode series resistance of the anode if the anode charge neutral thickness is 500E-4 cm?

$\mu_p = 300$ cm^2/V-sec

$$\therefore R = \frac{500\times10^{-4}-1.72\times10^{-2}}{A\cdot N_{A,eff}\cdot q\cdot\mu_p} = \frac{3.28\times10^{-2}}{1000E^{-8}\times10^{17}\cdot1.602\times10^{-19}\times300} = 682.48\Omega$$

Answer 2d[7] The anode resistance is approximately 682.48 Ohm.

e If the charge neutral region of the anode region is changed to 0.5E-4 cm. long, what does the saturation current density become?

Since $0.5E\text{-}4$ cm $< 1.71\times10^{-2}$ cm $\Rightarrow$ short diode

$$\therefore J = q n_i^2 \frac{D_n}{N_{A,eff}\cdot 0.5E^{-4}} = 1.602\times10^{-19}\times(1.45\times10^{10})^2 \frac{18.09}{10^{17}\times0.5\times10^{-4}} = 1.22\times10^{-10} \text{ A/cm}^2$$

=

Answer 2e[6] The saturation current density is 1.22×10^{-10} A/cm2.

3 A diode has a saturation current of 2E-14 A.

a Evaluate the diode current at 700 mV.

$$i_D = I_S\left(e^{\frac{V_a}{V_T}} - 1\right)$$
$$= 2E{-}14\left(e^{\frac{700}{25.843}} - 1\right)$$
$$= 0.0116A = 11.6mA$$

Answer 3a[6] The diode current is 11.6mA mA.

b Evaluate the diode conductance at 700 mV.

$$g_d = \frac{i_D}{V_t} = \frac{11.6mA}{0.025843V} = 449.0$$

Answer 3b[6] The diode conductance is 449.0 mA/V.

c The diode is a p+n diode with n = 3E14/cm^3 in the ("long" and uncompensated) cathode region. What is the diffusion capacitance of this diode at 700 mV.

$$\tau_{min} = \frac{4.5\times10^{-5}}{1 + \frac{N_i}{10^{17}} + \left(\frac{N_i}{5\times10^{17}}\right)^2} = 4.49\times10^{-5} \text{ Sec.}$$

$$\therefore C_{diff} = g_d\,\tau_{min} = 2.0154\times10^{-5}$$

Answer 3c[7] The diffusion capacitance is 2.0154×10^{-5} Fd.

d Using the procedure of Massobrio and Antognetti, at what voltage across the depletion region will the diode transition from low-level to high-level injection?

$$V_{KF} \doteq 2V_T \ln\left(\frac{2N_d}{n_i}\right) = 2\times0.025843\times\ln\left(\frac{2\times3\times10^{14}}{1.45\times10^{10}}\right)$$
$$= 0.5136V = ~~513.6mV~~$$

549.44

549.44

Answer 3 d[6] The transition from low-level to high-level injection is at 513.6 mV.

e If this diode has a planar junction (essentially no junction curvature), solve for the breakdown voltage.

$$V_B = 60\left(\frac{E_g}{1.1}\right)^{\frac{3}{2}}\left(\frac{10^{16}}{N_B}\right)^{\frac{3}{4}} \quad \text{where } N_B = 3E14,\ E_g = 1.124V$$
$$\Rightarrow 60\left(\frac{1.124}{1.1}\right)^{\frac{3}{2}}\left(\frac{10^{16}}{3\times10^{14}}\right)^{\frac{3}{4}} = 859.75\,V$$

Answer 3 e[6] The breakdown voltage is 859.75 V.