Test 2-EE 5340/001&051 (print last name) ___**Solution**___ (print first name)______________________

Thursday, October 29, 2003, 8:00 AM, 206 Activities Building

75 minutes allowed (last four digits of your student #) _____________ (e-mail if new)______________________

Seat Number _______________ Enrolled in (circle one) 8:00 AM or 9:30 AM class

Instructions:

1. Do your own work. DO NOT REMOVE THE STAPLE ON THIS EXAM.
2. You may use either a legal copy of the text OR reference text. You may NOT pass a book or note sheet to another student. You may NOT use class notes. Do not use previously solved problems.
3. Calculator allowed. You may NOT share a calculator with another student.
4. Use values given on this cover sheet. 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 $cm^2/V\text{-}sec$.
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 $cm^2/V\text{-}sec$.
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 $cm^2/V\text{-}sec$.
    (In 12 through 16, N_i = the total impurity concentration in n- or p-type material, compensated or not).
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.

1 A JFET is fabricated using a p$^+$ gate ($N_a = 8E18$ cm^{-3}) and an n-channel ($N_d = 4E15$ cm^{-3}, phosphorous). The available channel thickness (from the p$^+$n junction to the channel to substrate depletion region (i.e., $x_d + x_w \sim t$ in Figure 4.19 in M&K 3rd edition) is 0.8 µm. The channel length is 5 µm and the channel width is 9 µm.

a Calculate $\phi_i - V_T$ (where V_T or V_P is the turn-off voltage, and $\phi_i = V_{bi}$) for this device.

```
Assume W ~ xn since Na >> Nd
 PHIi - VT = q*4e15*(0.8e-5)^2/(2*epsSi*eps0)
 PHIi - VT = 1.979 V
```

a [6] $\phi_i - V_T$ = ______________________ V.

b Calculate G_0 (the open channel conductance) for this device.

```
SIGMAn = n*q*Mun = 4e15*q*((1414/(1+(4e15/9.2E16)^0.711))+68.5)
SIGMAn = 0.8620 /(Ohm-cm)
G0 = SIGMAn*W*t/L = SIGMAn*0.8e-4*9/5 = 0.1241 mA/V
```

b [6] G_0 = ______________________ mA/V.

c Calculate ϕ_i for this device.

```
PHIi = Vt*ln(Na*Nd/ni^2) = Vt*ln(8e18*4e15/ni^2)
PHIi = 844 mV
```

c [6] ϕ_i = ______________________ mV.

d Calculate $I_{Dsat0} = I_{Dsat}$ (for $V_G = 0$) for this device.

```
IDsat0 = G0*((PHIi-VT)/3 - PHIi*(1 - (2/3)*(PHIi/(PHIi-VT))^0.5))
IDsat0 = 2.27E-02 mA
```

d [7] I_{Dsat0} =______________________ mA.

2 An n-type wafer with ϕ_n = 234 mV has a planar diode constructed with N_a = 3E18 cm^{-3} in the p-region.
a Find the breakdown voltage (BV) for this diode assuming BV > ϕ_i = V_{bi}.

```
Nd = ni*e^(PHIn/Vt) = ni*exp(234/Vt) = 1.241E+14 cm^-3
This is much less than Na, so Nd = NB is the lightly doped side.
VB =  60*((EgSi/1.1)^(3/2))*(1e16/NB)^(3/4) V
VB =  60*((EgSi/1.1)^(3/2))*(1e16/1.241e14)^(3/4) V
VB =  1.67E+03 V
```

a [6] V_{BV} = ______________________ V.

b What is the depletion width at breakdown for this device?

```
W = sqrt(2*eps0*epsSi(PHIi-Va)/(q*(Na*Nd/(Na+Nd))))
At breakdown, VB = PHIi - Va = 1.67E3 V
W = sqrt(2*eps0*epsSi(1.667E3)/(q*(3E18*1.241E14/(3E18+1.241E14))))
At breakdown, W = 1.318E-02 cm
```

b [7] $W_{breakdown}$ = ______________________ cm.

3 A silicon sample with N_d = 7E15 cm^{-3} has traps at E_T = E_{fi} with a concentration of 8E14 cm^{-3}. The capture cross sections for the traps are σ_n = σ_p = 3E-15 cm^2 Let v_{th} = 1.5E7 cm/s.
a Calculate the minority carrier generation rate in a region which is depleted of mobile carriers.

```
For ET = Efi, the recombination rate becomes
G = -U = -(np - ni^2)/((p+n+2*ni)*TAU0)
TAU0 = (NT*SIGMA*vTh)^-1
TAU0 = (8E14*3E-15*1.5E7)^-1 = 2.778E-08 sec
n = p = 0, so G = ni/(2*TAU0) =2.610E+17 cm^-3 sec^-1
```

a [6] U = ______________________ cm^{-3}-sec^{-1}.

b Calculate the minority carrier generation rate in a region where the majority carrier concentration is essentially at the equilibrium value, but the minority carrier concentration is essentially zero.

```
n = Nd = 7E15, p = 0, so
G =-U = -(np - ni^2)/((p+n+2*ni)*TAU0) = -(- ni^2)/((7E15+2*ni)*TAU0)
G = 1.081E+12 cm^-3 sec^-1
```

b [6] U = ______________________ cm^{-3}-sec^{-1}.

4 An ideal, planar p^+n diode has N_a = 8E18 cm^{-3}, and N_d = 6E16 cm^{-3} with no compensation in either region. The n-region measures 5E-4 cm from junction to contact.

a Calculate the minority carrier diffusion coefficient for the n-region.

In the n-region, the minority carriers are holes, and Ni = Nd = 6E16,
Dmin = Mup*Vt
Mup = MUpB= (470.5/(1+(6E16/2.23E17)^0.719))+44.9
Dmin = 9.914 cm^2/sec

a [6] D_{min} = ____________________ cm^2/sec.

b Calculate the minority carrier diffusion length for the n-region.

Lmin = sqrt(Dmin*TAUmin) = sqrt(Dmin*((45E-6)/(1+6E16/1E17+(6E16/5E17)^2)))
Lmin = 1.662E-02 cm

b [6] L_{min} = ______________________ cm.

c Calculate the saturation current density for the lightly doped side.

Since Lmin >> the dimension of the n-region, let Lmin*tanh(Wn/Lmin) = Wn
Wn = 5E-4 cm - xn, where xn is the DR on the n-side ~ W, the total D.R.
PHIi = Vt*ln(Na*Nd/ni^2) = Vt*ln(8E18*6E16/ni^2) = 913.9 mV
At Va = 0, W ~ sqrt(2*eps0*epsSi*PHIi/(q*6E16) = 1.404E-05 cm
Wn = 5E-4 - 1.404E-5 =4.860E-04 cm
Js = q*ni^2*Dmin/(Nd*4.86E-4) = 1.145E-11 A/cm^2

c [7] J_s = ____________________ A/cm^2.

d Calculate the small-signal resistance for the diode at V_a = 30 V_t. Assume the contribution due to the heavily doped side is negligible. Assume the diode junction area is 1e-4 cm^2.

Id = Js*A*expf(Va/Vt) = 1.145E-11*1E-4*(exp(30)-1) = 1.224E-02 A
rd = Vt/Id = 2.112Ohm

d [6] r_d = ____________________ Ohm.

5 An ideal prototype BJT structure has N_{dE} = 1E19 cm^{-3}, N_{aB} = 5E16 cm^{-3}, N_{dC} = 1E15 cm^{-3}, with no compensation in any region. Assume the charge neutral base width is 0.8E-4 cm. The emitter area and collector areas are 100E-8 cm^2. Assume phosphorous parameters when electron minority carrier values are needed.

a Calculate the emitter efficiency for this BJT. You may assume D_{min} for the emitter is 1.5 cm^2/sec and that the emitter charge neutral region width is the same as the base.

```
Dbmin = Mun(Phos)*Vt = ((1414/(1+(5E16/9.2E16)^0.711))+68.5)*Vt
      =23.94 cm2/sec
gamma = (1+NB*DE*XB/(NE*DB*XE))^-1
      = (1+5E16*1.5*0.8E-4/(1E19*23.94*0.8E-4))^-1
gamma = 0.99969
```

a [7] γ = ____________________ .

b Calculate the base transport factor for this device.

```
TAUminB = (45E-6)/(1+5E16/1E17+(5E16/5E17)^2) = 2.980E-05 sec
LminB = sqrt(Dbmin*TAUmin) = 2.671E-02 cm
alphaT = (1+xB^2/(2*LminB^2))^-1 = 0.9999955
```

b [6] α_T = ______________________ .

c Calculate the IS parameter for this device.

```
IS = q*ni^2*A*Db/(Nb*xB) = q*ni^2*100E-8*23.94/(5E16*0.8E-4)
IS =  2.016E-16 A
```

c [6] IS = ____________________ A.

d Calculate the β_F parameter for this device.

```
alphaF = gamma*alphaT*delta, assume delta = 1
betaF = alphaF/(1-alphaF) = gamma*alphaT/(1-gamma*alphaT)
betaF = 0.99969*0.9999955/(1-0.99969*0.9999955) = 3179
```

d [6] β_F = ____________________ .