

Test 3-EE 5340/001&051 (print last name) _____ (print first name) KEY
 Tuesday, November 12, 2002, 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 OR ONE sheet of hand-written notes. 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,

$$T = 300\text{K}, \quad V_t = 25.852 \text{ mV}$$

10. Unless otherwise stated, the material is silicon with

$n_i = 1.07\text{E}10 \text{ cm}^{-3}$	$N_c = 2.84\text{E}19 \text{ cm}^{-3}$	$q\chi_{\text{Si}} = 4.05 \text{ eV}$
$E_{g,\text{Si}} = 1.125 \text{ eV}$	$N_v = 3.08\text{E}19 \text{ cm}^{-3}$	

11. For the work function of poly silicon, use

$$\phi_{n+} = \chi_{\text{Si}} = 4.05 \text{ V}$$

$$\phi_{p+} = \chi_{\text{Si}} + E_{g,\text{Si}}/q = 5.175 \text{ V}$$

12. For minority carrier (either electrons or holes) lifetime in silicon, use the relationship

$$\tau_{\text{min}} = (45\text{E}-6 \text{ sec}) / (1 + 7.7\text{E}-18 * N_{\text{imp}} + 4.5\text{E}-36 * N_{\text{imp}}^2),$$

where N_i = the total impurity concentration

13. For holes in silicon, assume

$$\mu_p = \{418.3 \div [1 + (N_i \div 1.6\text{E}17)^{0.7}] + 49.7\}, \text{ in cm}^2/\text{V-sec}$$

(where N_i = the total impurity concentration in n- or p-type material, compensated or not).

14. For electrons in silicon, assume

$$\mu_n = \{1268 \div [1 + (N_i \div 1.3\text{E}17)^{0.91}] + 92\}, \text{ in cm}^2/\text{V-sec}$$

(where N_i = the total impurity concentration in n- or p-type material, compensated or not).

15. Metal gate work functions should be assumed to be

$$\phi_{\text{Au}} = 4.75 \text{ V for gold}, \quad \phi_{\text{Al}} = 4.1 \text{ V for aluminum.}$$

16. The electron affinity of SiO_2 is $\chi_{\text{SiO}_2} = 0.95 \text{ V}$.

17. Planck constant $h = 6.62618 \times 10^{-34} \text{ J-s} = 4.1354 \times 10^{-15} \text{ eV-s}$, $1 \text{ eV} = 1.60218 \times 10^{-19} \text{ Joule}$

18. free electron mass $m_o = 9.1095 \times 10^{-28} \text{ g}$.

19. Boltzmann constant, $k = 1.38066 \times 10^{-23} \text{ J/K}$

20. Electron charge, $q = 1.60218 \times 10^{-19} \text{ Coulomb}$

21. Permittivity of free space, $\epsilon_o = 8.85418 \times 10^{-14} \text{ Fd/cm}$

22. Relative permittivity of silicon, $\epsilon_r = 11.7$

23. The breakdown voltage of an abrupt (step) junction (assymetrical or one-sided) diode with doping on the lightly doped side of N_B is $V_B = 60(E_g/1.1)^{3/2} (10^{16}/N_B)^{3/4} \text{ V}$.

24. Each part is worth [x] points, as given in the problem.

1. For this problem, consider the Schottky diode to be ideal with no boundary layer, interface states or barrier lowering due to image effects. The semiconducting substrate is silicon with a donor concentration of $2 \times 10^{16} \text{ cm}^{-3}$. The gate material is gold (Au).

a. Calculate the barrier height for electrons passing from gold to silicon, $q\phi_{Bn}$.

$$\begin{aligned} \phi_{Bn} &= \phi_{Au} - \chi_{Si} \\ q\phi_{Bn} &= 0.70 \text{ eV} \end{aligned}$$

Answer a [6]: $q\phi_{Bn} = \underline{\hspace{2cm}}$ eV.

b. Calculate the barrier height for electrons passing from silicon to gold, qV_{bi} .

$$\begin{aligned} N_d &= 2.00 \times 10^{16} \text{ cm}^{-3} \\ V_{bi} &= \phi_{Au} - \phi_{Si} \\ \phi_{Si} &= \chi_{Si} + V_t \ln(N_c/n_d) \\ &= 4.238 \text{ V} \\ V_{bi} &= 0.512 \text{ eV} \end{aligned}$$

Answer b [6]: $qV_{bi} = \underline{\hspace{2cm}}$ eV.

c. Calculate the depletion region width for this junction when $V_a = 0 \text{ V}$.

$$\begin{aligned} W &= \sqrt{2 \epsilon_0 \epsilon_{rSi} V_{bi} / (q N_d)} \\ &= 1.82 \times 10^{-5} \text{ cm} \end{aligned}$$

Answer c [6]: $W = \underline{\hspace{2cm}}$ cm.

d. Assume the Richardson constant $A^* = 250 \text{ A-cm}^{-2}\text{K}^{-2}$. Calculate the saturation current density J_{sT} for this junction.

$$\begin{aligned} A^* &= 250 \text{ Amp/cm}^2\text{K}^2 \\ J_{sT} &= A^* T^2 \exp(-\phi_{Bn}/V_t) \\ J_{sT} &= 3.91 \times 10^{-5} \text{ Amp/cm}^2 \end{aligned}$$

Answer d [6]: $J_{sT} = \underline{\hspace{2cm}}$ A-cm^{-2} .

e. A diode is constructed with this gold-silicon system. The area of the diode is $400 \times 10^{-8} \text{ cm}^2$. The total junction capacitance is measured as a function of the diode voltage for $-0.5 < V_a < 0.1 \text{ V}$. A plot of C_j^{-2} vs. V_a is made. What is the value of the extrapolated intercept, $V_{a,}$ of this plot with the voltage axis?

The intercept on the voltage axis would be $V_{bi} = 0.513 \text{ V}$

Answer e [6]: $V_{a,} = \underline{\hspace{2cm}}$ V.

2. For this problem, consider a **hypothetical** semiconductor material with $n_i = 4.00E+10/cm^3$ and a relative permittivity of 10. Consider the charge neutral region width for each region to be the same as when the junction voltages, $v_{BE} = 0$ and $v_{BC} = 0$, unless otherwise stated.

- The emitter (n-type) region has $|N| = 8.00E+18/cm^3$ (no compensation), $D_{min} = 8 \text{ cm}^2/\text{sec}$ and $\tau_{min} = 3E-8$ sec, and is $0.5E-4$ cm wide from junction to contact.
- The base (p-type) region has $|N| = 5.00E16/cm^3$ (no compensation), $D_{min} = 25 \text{ cm}^2/\text{sec}$ and $\tau_{min} = 6E-7$ sec, and is $0.5E-4$ cm wide from emitter-base junction to collector-base junction.
- The collector (n-type) region has $|N| = 2.00E+15/cm^3$ (no compensation), $D_{min} = 35 \text{ cm}^2/\text{sec}$ and $\tau_{min} = 2E-6$ sec, and is $2E-4$ cm wide from junction to contact.

a. Calculate the depletion region width, W_E , at the EB junction.

$$\begin{aligned}
 q &= 1.60E-19 \\
 n_i &= 4.00E+10 & \epsilon_r &= 10 & \epsilon_o &= 8.85E-14 & V_t &= 0.025852 \\
 N_E &= 8.00E+18 & D_E &= 8 & \tau_E &= 3.00E-08 & w_E &= 5.00E-05 \\
 N_B &= 5.00E+16 & D_B &= 25 & \tau_B &= 6.00E-07 & w_B &= 5.00E-05 \\
 N_C &= 2.00E+15 & D_C &= 35 & \tau_C &= 2.00E-06 & w_C &= 2.00E-04
 \end{aligned}$$

$$\begin{aligned}
 V_{biE} &= V_t \cdot \ln(N_E \cdot N_B / n_i^2) = 0.857 \text{ V} \\
 W &= \text{SQRT}(2 \cdot \epsilon_r \cdot \epsilon_o \cdot V_{biE} / (q \cdot N_B \cdot N_E / (N_B + N_E))) = 1.38E-05 \text{ cm}
 \end{aligned}$$

Answer a [6]: $W_E =$ _____ cm.

b. Calculate the depletion region width, W_C , at the CB junction.

$$\begin{aligned}
 V_{biC} &= V_t \cdot \ln(N_C \cdot N_B / n_i^2) = 0.643 \\
 W &= \text{SQRT}(2 \cdot \epsilon_r \cdot \epsilon_o \cdot V_{biC} / (q \cdot N_B \cdot N_C / (N_B + N_C))) = 6.08E-05
 \end{aligned}$$

Answer b [6]: $W_C =$ _____ cm.

c.[8] Prove that the “short diode” equations are appropriate for the emitter and base regions.

The fraction of the EB depletion region in the emitter is

$$\begin{aligned}
 x_E &= w_{EB} / (1 + N_E / N_B) = 8.57E-08 \text{ cm} \\
 L_E &= \text{SQRT}(D_E \cdot \tau_E) = 4.90E-04 \text{ cm} \\
 \text{The emitter cnr is } w_E - x_E &= 4.99E-05 \text{ cm} \ll L_E, \text{ so short}
 \end{aligned}$$

The fraction of the EB depletion region in the base is

$$x_{Bo} = w_{EB} / (1 + N_B / N_E) = 1.37182E-05 \text{ cm}$$

The fraction of the CB depletion region in the base is

$$x_{Co} = w_{CB} / (1 + N_B / N_C) = 2.33692E-06 \text{ cm}$$

$$L_B = \text{SQRT}(D_B \cdot \tau_B) = 3.87E-03 \text{ cm}$$

$$\text{The base cnr is } w_B - x_{Bo} - x_{Co} = 3.39E-05 \ll L_B, \text{ so short}$$

3. Considering the same material and device as problem 2:

a. In the forward active region, calculate the saturation current density, J_{nES} , for electrons at the EB junction.

$$\text{Since this is a "short" region, } J_{nES} = q \cdot n_i^2 \cdot D_B / (N_B \cdot x_B) \\ J_{nES} = 3.77596E-09 \text{ A/cm}^2$$

Answer a [6]: $J_{nE} = \underline{\hspace{2cm}} \text{ A/cm}^2$.

b. Calculate the saturation current density, J_{pES} , for holes at the EB junction.

$$\text{Since this is a "short" region, } J_{pES} = q \cdot n_i^2 \cdot D_E / (N_E \cdot x_E) \\ J_{pES} = 5.13578E-12 \text{ A/cm}^2$$

Answer b [6]: $J_{pE} = \underline{\hspace{2cm}} \text{ A/cm}^2$.

c. In the forward active region calculate the saturation current density, J_{nCS} , for electrons at the CB junction.

$$\text{The base current is reduced by a factor of } \alpha_T, \text{ so } J_{nCS} = \alpha_T \cdot J_{nES} \\ J_{nCS} = 3.77567E-09$$

Answer c [6]: $J_{nE} = \underline{\hspace{2cm}} \text{ A/cm}^2$.

d. For forward active region operation, calculate the emitter efficiency, γ .

$$\gamma = J_{nES} / (J_{nES} + J_{pES}) \\ \gamma = 0.99864$$

Answer d [6]: $\gamma = \underline{\hspace{2cm}}$.

e. For forward active region operation, calculate the base transport factor, α_T .

$$\alpha_T = 1 - (x_B / L_B)^2 \\ \alpha_T = 0.99996$$

Answer e [6]: $\alpha_T = \underline{\hspace{2cm}}$.

4. A silicon npn bjt has $N_E = 2E19/cm^3$, $N_B = 3E16/cm^3$, $N_C = 1E15/cm^3$, with no compensation in any region. The charge neutral region widths are $x'_E = 0.5E-4cm$, $x_B = 0.5E-4cm$, $x''_C = 2E-4cm$. For this emitter doping, the emitter bandgap is reduced by $\Delta E_g = 0.100 eV$.

a. For forward active region operation, calculate the emitter efficiency, γ .

doping conc (cm ⁻³)	cnr width (cm)	min carr lifetime(sec)	diff (cm ² /s)	diff l (cm)	type
NE = 2.00E+19	x'E = 5.00E-05	tauE = 2.30E-08	DpE = 1.6	LE = 1.94E-04	short
NB = 3.00E+16	xB = 5.00E-05	tauB = 3.64E-05	DnB = 28.3	LB = 3.21E-02	short
NC = 1.00E+15	x''C = 2.00E-04	tauC = 4.47E-05	DpC = 11.8	LC = 2.30E-02	short

$$\Delta E_g = 0.100 \text{ eV}$$

since ΔE_g is $> V_t$, NE in gamma is replaced by $NE/EXP(\Delta E_g/V_t)$

$$\gamma = 1/(1+(N_B * D_{pE} * x_B * EXP(\Delta E_g/V_t)/(N_E * D_{nB} * x_E)))$$

$$\gamma = 0.995859$$

Answer a [8]: $\gamma =$ _____ .

b. For forward active region operation, calculate the base transport factor, α_T .

$$\alpha_T = 1-(x_B/L_B)^{2/2}$$

$$\alpha_T = 0.999999$$

Answer b [6]: $\alpha_T =$ _____ .

c. For forward active region operation, and assuming negligible recombination/generation in the depletion regions, calculate the current gain factor, β_F .

$$\alpha_F = \gamma * \alpha_T$$

$$\alpha_F = 0.995858$$

$$\beta_F = \alpha_F/(1-\alpha_F)$$

$$\beta_F = 240$$

Answer c [6]: $\beta_F =$ _____ .