Course:	**Semiconductor Device Fundamentals**
Level:	**Undergraduate**
Module:	**C**
Test:	**C5**
Type:	***Open* Book, *Open* Notes**

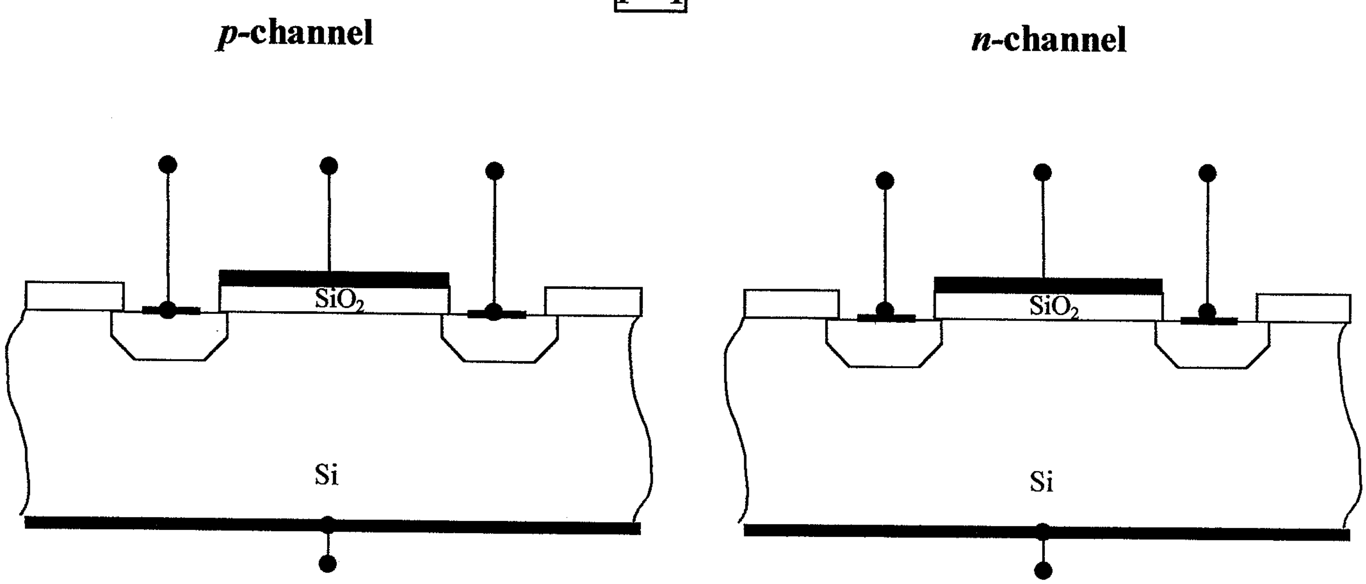
Problem Weighting--- **Part A--Transistors**

F-1...25 (a-20, b-5)
F-2...25 (a-15, b-5, c-5)
F-3...50 (a-25, b-5, c-7, d-8, e-5)

Part B--Fundamentals and Diodes
(Optional--possible T1 or T2 replacement
Weighting adjacent to problems)

PART A...TRANSISTORS

F – 1



(a) Two partially completed MOSFET cross-sections are pictured above. When completed, the figure on the left is to correspond to a *p*-channel MOSFET; the figure on the right, to an *n*-channel MOSFET. Complete the figures as directed below.

(i) Insert the appropriate doping type (*n* or *p*) in the silicon substrate region.

(ii) Insert the appropriate doping type (*n*+ or *p*+) in the source/drain regions.

(iii) Label the gate, source, drain, and back leads G, S, D, and B, respectively.

(iv) Identify the leads that are typically grounded.

(v) Place the gate voltage symbol, V_G, adjacent to the appropriate lead AND indicate the polarity (≥ or ≤) of V_G that must be applied to the gate to achieve inversion biasing if the transistors are assumed to be ideal.

(vi) Place the drain voltage symbol, V_D, adjacent to the approporiate lead AND indicate the polarity (≥ or ≤) of V_D under normal operating conditions.

(vii) Using appropriately directed arrows and ● (for electrons) and O (for holes), skematically indicate the direction of carrier motion in the surface channel.

(viii) Note the direction of positive drain current (I_D); i.e., draw a properly directed arrow labeled I_D next to the drain lead.

(ix) Taking the <u>p-channel</u> MOSFET to be inversion biased but $V_D = 0$, and using a dashed line, roughly outline the shape of the depletion regions inside the transistor.

(x) Taking the <u>n-channel</u> MOSFET to be biased into the saturation region of operation, and using a dashed line, roughly outline the shape of the depletion regions inside the transistor.

(Continued)

(b) Suppose an ideal *n*-channel MOSFET and an ideal *p*-channel MOSFET are fabricated with the same gate oxide thickness, the same channel dimensions, and the same substrate doping concentration (either N_A, or N_D, as appropriate). With the same inverting $|V_G - V_T|$ applied to the gate, how will the observed $|I_{Dsat}|$ of the two transistors compare? You must justify your answer to receive credit.

F – 2

In simulation programs like SPICE, a modified "bulk-charge" theory is often introduced where one approximates the charge in an n-type channel to be

$$Q_N(y) = -C_o(V_G - V_T - a\phi)$$

where a = constant ≥ 1. Employing the $Q_N(y)$ relationship given above, derive expressions for:

(a) I_D below pinch-off as a function of V_G and V_D

(b) V_{Dsat}

(c) I_{Dsat}

Express your answers in the simplest form possible and put a box around your final answers.

F – 3

A *pnp* BJT maintained at $T = 300K$ and characterized by the parameters in the table† below is active mode biased with $V_{EB} = 0.5V$ and $V_{CB} = -20V$.

Emitter	*Base*	*Collector*
$N_E = 10^{18}/cm^3$	$N_B = 10^{16}/cm^3$	$N_C = 10^{15}/cm^3$
$\mu_E = 263\ cm^2/V\text{-}sec$	$\mu_B = 437\ cm^2/V\text{-}sec$	$\mu_C = 1345\ cm^2/V\text{-}sec$
$D_E = 6.81\ cm^2/sec$	$D_B = 11.3\ cm^2/sec$	$D_C = 34.8\ cm^2/sec$
$\tau_E = 10^{-7}$ sec	$\tau_B = 10^{-6}$ sec	$\tau_C = 10^{-6}$ sec
$L_E = 8.25 \times 10^{-4}$ cm	$L_B = 3.36 \times 10^{-3}$ cm	$L_C = 5.90 \times 10^{-3}$ cm
	$W_B = 2 \times 10^{-4}$ cm	

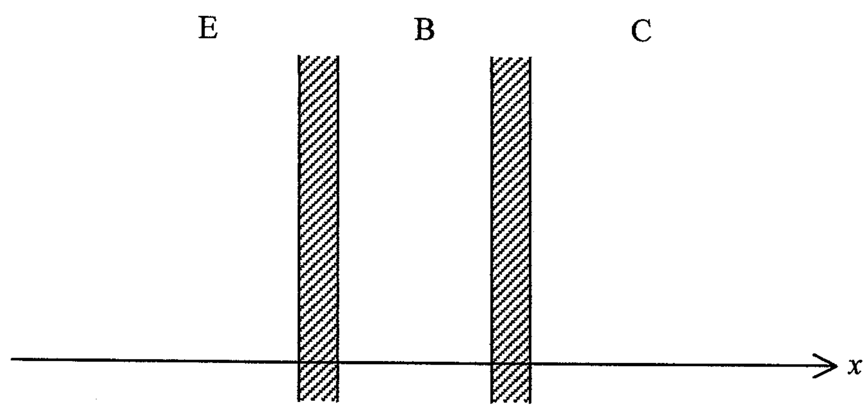
(a) Taking into account the true quasineutral width of the base in performing calculations, determine the common emitter gain (β_{dc}) of the transistor at the given operating point.
NOTE: You are **NOT** to assume $W = W_B$. To receive full credit you must show all substeps and substep calculations in leading to your answer.

† Table reproduced from *PIERRET, ROBERT F., SEMICONDUCTOR DEVICE FUNDAMENTALS, 1st Edition, © 1996. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ.*

(Continued)

(b) The α_F parameter appearing in the Eber-Moll equations and model is known as the forward current gain. What is the α_F for the given transistor and biasing condition?

(c) On the linear scale included below, sketch the perturbed minority carrier distributions normalized to the equilibrium carrier concentrations ($\Delta n_E/n_{E0}$, etc.) in the quasineutral regions of the emitter, base, and collector for the given biasing condition. Specify all values of the normalized perturbed carrier concerntrations ($\Delta n_E/n_{E0}$, etc.) at the depletion region edges.



(Continued)

(d) When operated in the common base configuration, will the given transistor exhibit a maximum $-V_{CB}$ limited by punch-through or avalanche breakdown? Justify your answer.

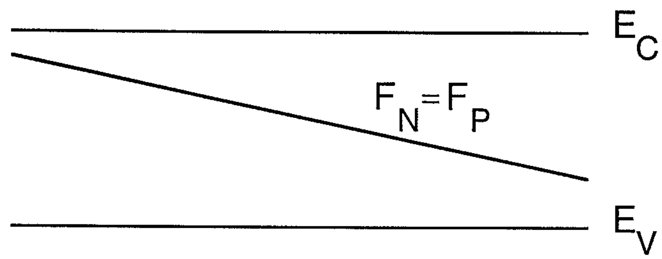
(e) Indicate how you would go about estimating the expected V_{CE0} of the given transistor. (An actual numerical calculation is not required.)

PART B..FUNDAMENTALS AND DIODES

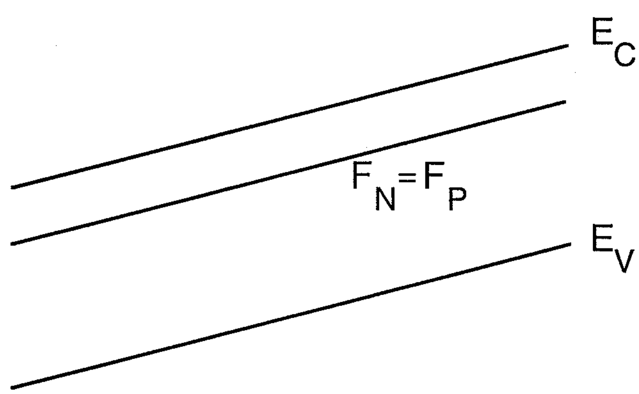
(Optional…possible T1 or T2 replacement)

1. <u>Carrier Action</u> (5 points each, 20 points total)

For each situation illustrated below, place a check mark in every box that applies. For each question, you may place as many check marks as you feel appropriate. Hint: The electron and hole densities are related to the quasi-Fermi levels F_N and F_P by eqn. (3.71), p. 132 in the text.



- ☐ Diffusion is occurring
- ☐ Drift is occurring
- ☐ Recombination >> Generation
- ☐ Generation >> Recombination
- ☐ The sample is in equilibrium



- ☐ Diffusion is occurring
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- ☐ Recombination >> Generation
- ☐ Generation >> Recombination
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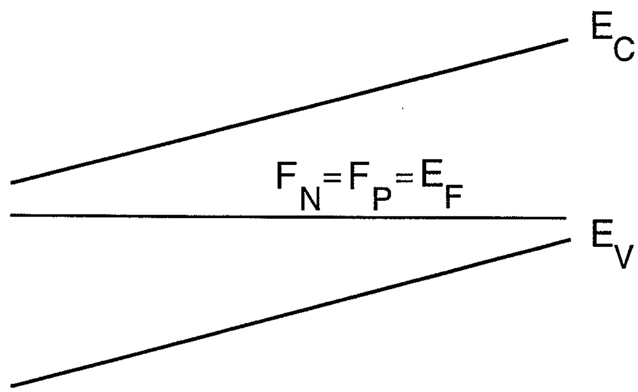
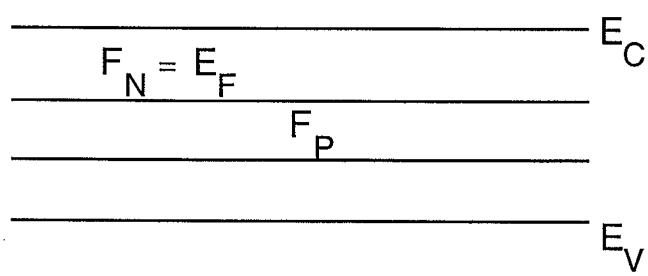


- [ ] Diffusion is occurring
- [ ] Drift is occurring
- [ ] Recombination >> Generation
- [ ] Generation >> Recombination
- [ ] The sample is in equilibrium



- [ ] Diffusion is occurring
- [ ] Drift is occurring
- [ ] Recombination >> Generation
- [ ] Generation >> Recombination
- [ ] The sample is in equilibrium

2. Carrier Concentration Calculations (10 points total)

2.A A silicon sample is uniformly doped with 10^{17} donors and $5x10^{16}$ acceptors per cm^3. The sample is maintained at a high temperature such that the intrinsic carrier concentration is $2.5x10^{16}$ cm^{-3}. What is the equilibrium electron density at this temperature?

(5 points)

2.B What is the equilibrium hole density at this temperature?

(5 points)

3. Diffusion Currents in a Neutral Region (25 points total)

3.A A uniformly-doped n-type semiconductor bar has a surface at x = 0, and extends in a semi-infinite fashion toward $x = \infty$. Minority carrier holes are injected at x = 0 such that the hole current density at x = 0 is $J_P(0)$. The entire bar is under low level injection, the electric field within the bar is negligible, no photogeneration takes place, and the bar is maintained at room temperature. Obtain an expression for the excess minority carrier density at x = 0 in steady state.

(10 points)

3.B Obtain an expression for the distance x_0 into the bar at which the hole current is half the value at $x = 0$.

(10 points)

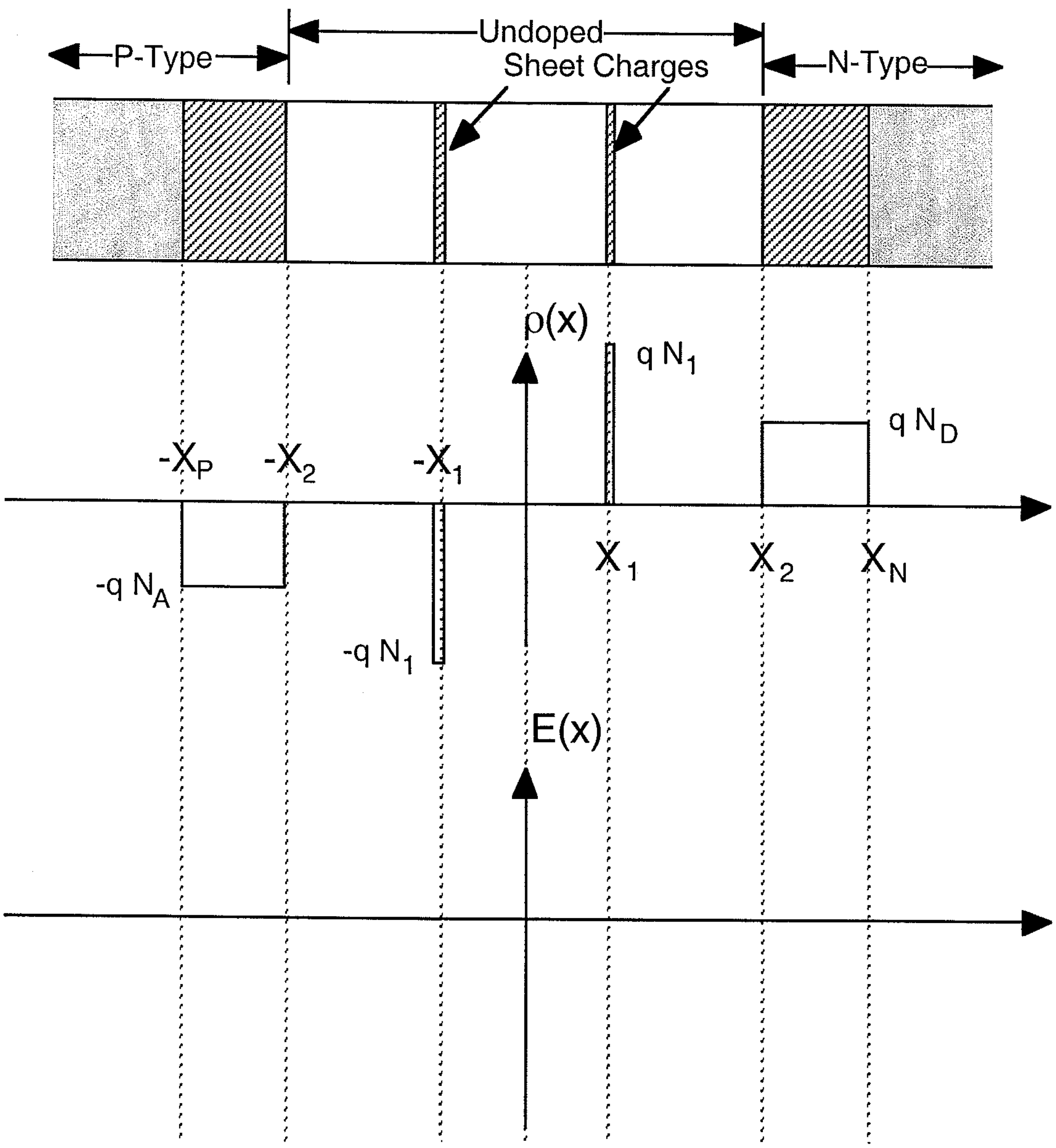
3.C Obtain an expression for the total number of electron-hole pairs recombining per unit area per second in the entire region $x > x_0$.

(5 points)

4. PN Junction Electrostatics (15 points total)

4.A A pn junction is fabricated with an unusual doping profile, as illustrated below. Specifically, a thin sheet of donor atoms in incorporated at $x = +x_1$ and a thin sheet of acceptor atoms at $x = -x_1$. The total number of donors (acceptors) per unit area in each sheet is N_1 atoms per cm^2. Otherwise, the region between $-x_2$ and $+x_2$ is undoped. The region $x > x_2$ is uniformly doped with N_D donors per cm^3 and the region $x < -x_2$ is uniformly doped with N_A acceptors per cm^3. The pn junction is biased such that the regions between $x=-x_P$ and $x=+x_N$ are totally depleted of carriers. The resulting charge diagram is drawn below. Sketch (in the space provided) the electric field as a function of x within the region $-x_P < x < +x_N$.

(10 points)



4.B Obtain an expression for the maximum electric field in the depletion region in terms of the dopings, dimensions, and charges given in the diagram of part A.

(5 points)

5. PN Junction Current (5 points each, 20 points total)

Consider a pn step junction under forward bias V_1, producing a steady-state current density J_1. The ohmic contacts are very far from the edge of the depletion region, low level injection conditions prevail, the diode is not illuminated, and generation-recombination in the depletion region is negligible (unless otherwise stated).

5.A If the doping on both sides of the junction is increased by a factor of 10, what is the new current density J_2?

5.B Returning to the original diode having current density J_1, if the number of generation-recombination centers on both sides of the junction is increased by a factor of 100, what is the new current densityJ_2?

5.C Returning again to the original diode having current density J_1, if the bandgap energy of the semiconductor on both sides of the junction is increased by 100 meV, what is the new current density J_2?

5.D Finally, considering again the original diode biased at $V_A = V_1$, if we introduce recombination centers within the depletion region such that the recombination rate within the depletion region is R_1 electron-hole pairs per unit volume per second, and the width of the depletion region under forward bias V_1 is W_1, what is the new current density J_2?

6. MS Diodes (5 points each, 10 points total)

6.A An MS diode is formed on silicon. The metal work function is 4.5 eV. For simplicity, assume the electron affinity of silicon is 4.0 eV. If the silicon is uniformly doped with 5×10^{16} cm^{-3} donors, calculate the built-in potential of this junction at room temperature.

6.B What is the maximum electric field in the above junction in equilibrium?