



BAŞKENT UNIVERSITY

Department of Electrical and Electronics Engineering

EEM 214 ELECTRONICS

Spring 2005-06

MIDTERM EXAM

Date: April 14, 2006

Hour: 11:00

Duration: 110 minutes

IMPORTANT: READ BEFORE STARTING

- There are five questions, attempt all.
- Use the reserved space to answer each question. Written material outside the reserved space will not be considered for credit.
- Show complete work for full credit.
- Include units in your answers.
- You have more than sufficient time to answer the questions. Read the questions carefully, organize your work and write legibly.
- If you are asked to **DERIVE** an expression, you must **DERIVE** it starting from the basic laws and showing your complete work in order to get credit.

GOOD LUCK

Surname :

Name :

Student No :

Question	Points	Score
1	20	
2	20	
3	20	
4	20	
5	20	
TOTAL	100	

Useful Material

Boltzmann's constant	$k = 1.38 \times 10^{-23} \text{ J/K}$ $= 8.62 \times 10^{-5} \text{ eV/K}$
Electronic charge	$q = 1.6 \times 10^{-19} \text{ C}$
Room temperature value of kT	$= 0.0259 \text{ eV}$
$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$	
$n_i = 10^{10} \text{ cm}^{-3}$ at 300K	
Planck's constant	$h = 6.626 \times 10^{-34} \text{ Jsec}$
Velocity of light	$c = 3 \times 10^8 \text{ m/sec}$

Semiconductor	$E_g(\text{eV})$
Carbon	5.47
Silicon	1.12
Germanium	0.66
Gallium Arsenide	1.42

$$n_i^2 = BT^3 e^{\left(-\frac{E_g}{kT}\right)}$$

$$(N_D \gg N_A) \Rightarrow n = \frac{(N_D - N_A) \pm \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2}$$

$$(N_A \gg N_D) \Rightarrow p = \frac{(N_A - N_D) \pm \sqrt{(N_A - N_D)^2 + 4n_i^2}}{2}$$

$$n = n_i e^{(E_F - E_i)/kT}$$

$$p = n_i e^{(E_i - E_F)/kT}$$

$$qV_0 = q \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$$

$$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} - \frac{\delta_p}{\tau_p}$$

$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} - \frac{\delta_n}{\tau_n}$$

Q.1. (20 pts) CIRCLE the your answer for the questions in this part (4 FALSE answer will cancel 1 correct answer).

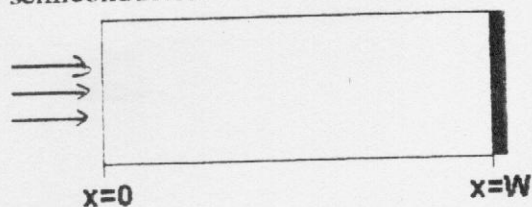
- (1) For an intrinsic semiconductor, which one of the following is **wrong**?
- (a) there are no charge carriers at 0°K ,
 - (b) the number of charge carriers is a function of temperature,
 - (c) electron concentration in the conduction band is equal to the concentration of holes in the valence band.
 - ☒ (d) the energy required to break the covalent bond is less than the band gap energy,
- (2) Which one of the following is **wrong**?
- (a) Column V elements behave as donors in Si,
 - (b) Column III elements behave as acceptors in Si,
 - (c) Compensation decreases the free carrier density,
 - ☒ (d) $n_i^2 = n \cdot p$ is valid ~~is~~ during carrier injection .
- (3) Which one of the following is **wrong**?
- (a) Fermi level has a probability of $\frac{1}{2}$ of being occupied by an electron, if no forbidden band exists,
 - (b) At 0°K every available state up to E_F is filled with electrons and all states above E_F are empty,
 - (c) Probability that a state ΔE above E_F is filled is equal to the probability that a state ΔE below E_F is empty,
 - ☒ (d) As the temperature increases, the Fermi-level approaches to the conduction band and the number of electrons in the conduction band increases.
- (4) Consider a semiconductor at thermal equilibrium. Which one of the following **does not occur** when the temperature is increased?
- (a) thermal energy increases,
 - (b) generation rate increases,
 - ☒ (c) recombination rate decreases,
 - (d) conductivity increases.
- (5) When an intrinsic semiconductor is heated, the Fermi level,
- (a) moves closer to the conduction band with an amount equal to the thermal energy,
 - (b) moves closer to the valance band with an amount equal to the thermal energy,
 - ☒ (c) location remains the same with respect to conduction and valance bands,
 - (d) moves above the conduction band with an amount equal to the thermal energy,
- (6) Which of the following is **wrong**?
- Applied voltage on a diode changes
- (a) the electrostatic potential barrier and the electric field within the depletion region,
 - ☒ (b) the doping concentrations,
 - (c) the current components at the junctions,
 - (d) energy band separation within the depletion region.

Q.1 continues on the next page

Q.1 continues from the previous page

- (7) Which of the following is **wrong**?
- (a) electron (particle) movement due to diffusion is in the opposite direction of the concentration gradient,
 - (b) hole current due to diffusion is in the opposite direction of the concentration gradient.
 - (c) the electron drift current is in the opposite direction of the potential gradient,
 - ☒ (d) the hole drift current is in the direction of the potential gradient.
- (8) Reverse saturation current of a pn-junction diode is independent of the applied voltage because
- (a) the electric field at the junction does not change,
 - (b) the mobility of the electrons increases in proportion to an increase in electric field,
 - ☒ (c) the drift currents in the depletion region are proportional to the minority carrier concentrations that are constant for a given temperature,
 - (d) the electrostatic potential barrier does not change,
- (9) Considering a pn-junction at equilibrium (with no external bias voltage), which one of the following is **wrong**?
- (a) Drift and diffusion currents for electrons cancel each other,
 - (b) Fermi level is constant,
 - ☒ (c) Neutral p and n sides of the diode are at the same electrostatic potential ,
 - (d) the electrostatic potential barrier does not change,
- (10) Which one of the following is not one of the **three dominant mechanisms for the base current** of a forward biased pnp transistor?
- (a) electrons lost to recombination in the base are supplied true the base contact,
 - (b) electrons injected into the collector junction are supplied by the thermal generation in the base,
 - (c) electrons injected into the forward biased emitter junction are supplied by the base contact,
 - ☒ (d) thermally generated electrons in the collector are swept into the base by the reverse biased collector junction.

Q.2. (20 points) Excess holes are injected into an n-type semiconductor bar from the left end ($x=0$) as shown below. This is a low level injection and the electric field inside the bar is zero. The injection maintains a constant (steady-state) excess hole concentration of Δp at the injection point ($\delta p(0) = \Delta p$ where δp is the excess hole concentration). At the other end of the bar there is a contact which absorbs the excess carriers ($\delta p(W) = 0$). τ_p is the hole recombination lifetime in the semiconductor.



a) (10 pts) Start from the continuity equation for holes, find the expression for the steady state excess hole density inside the bar for $W \gg L_p$ and sketch δp versus x . Show complete work.

Answer:

$$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p} \quad ; \text{ steady-state } 0 = -\frac{1}{q} \frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p} ;$$

$E=0 \Rightarrow$ the current is purely diffusion current $\Rightarrow J_p = -q D_p \frac{\partial p}{\partial x}$

$$\Rightarrow D_p \frac{\partial^2 \delta p}{\partial x^2} = \frac{\delta p}{\tau_p} \Rightarrow \frac{\partial^2 \delta p}{\partial x^2} = \frac{\delta p}{\frac{D_p \tau_p}{L_p^2}} \Rightarrow \delta p(x) = C_1 e^{x/L_p} + C_2 e^{-x/L_p}$$

$$\left. \begin{array}{l} \delta p(\infty) = 0 \\ \delta p(0) = \Delta p \end{array} \right\} \Rightarrow \left. \begin{array}{l} C_1 = 0 \\ C_2 = \Delta p \end{array} \right\} \Rightarrow \delta p(x) = \Delta p e^{-x/L_p}$$

b) (5 pts) Find the expression for the hole current at $x=0$.

Answer:

$$J_p = J_p^{\text{diff}} + J_p^{\text{drift}} = -q D_p \frac{\partial p}{\partial x} \quad \text{and} \quad D_p = \mu_p \cdot V_T$$

$$\frac{\partial p}{\partial x} = \frac{\partial \delta p}{\partial x} = \frac{\partial \delta p(x)}{\partial x} \Big|_{x=0} = -\Delta p \frac{1}{L_p} e^{-x/L_p} \Big|_{x=0} = -\frac{\Delta p}{L_p} \Rightarrow J_p \Big|_{x=0} = \frac{q \cdot D_p \cdot \Delta p}{L_p}$$

c) (5 pts) Now assume that $\tau_p = \infty$ and repeat a and b. Show complete work.

Answer:

When $\tau_p = \infty$ there will be no recombination.

At steady-state $\delta p(0) = \Delta p = \delta p(x) = \delta p(W)$.

$J_p = 0$ since the concentration is uniform.

Q.3. (20 points) Suppose that you are making measurements on a rectangular, 0.1mm long sample of an unknown semiconductor at 300°K. The sample is uniformly doped with 10^{14} donor atoms/cm³ and all the donor atoms are ionized at 300°K. There are no acceptors present in the semiconductor. The intrinsic carrier concentration at 300°K is 5×10^{13} /cm³. When you apply 1.25V across the sample, you obtain a current density of 10A/cm².

a.) (5 points) Determine the equilibrium electron and hole concentrations in the semiconductor at 300°K. as accurately as possible.

Answer:

$$N_D = 10^{14} / \text{cm}^3$$

$$n_i = 5 \times 10^{13} / \text{cm}^3$$

$$N_A = 0 / \text{cm}^3$$

Since N_D is not much larger than $n_i \Rightarrow n \neq N_D$

$$\therefore n_o = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2} = 1.207 \times 10^{14} / \text{cm}^3$$

$$p_o = \frac{n_i^2}{n_o} = \frac{2.5 \times 10^{27}}{1.207 \times 10^{14}} = 2.071 \times 10^{13}$$

b.) (5 points) Neglect the contribution of the holes to the conductivity and calculate the electron mobility in the doped semiconductor at 300°K.

Answer:

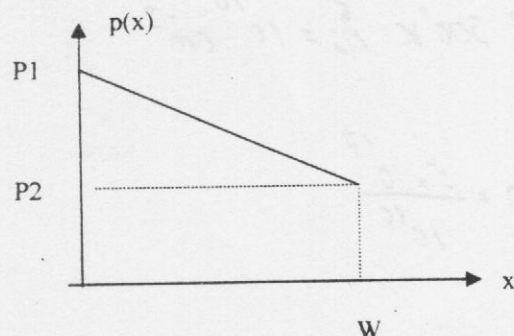
$$\sigma = q \cdot n \cdot \mu_n$$

$$\sigma = 0.08 \Omega^{-1} \text{cm}^{-1} \Leftarrow J = \sigma \cdot E = 10 \text{ A/cm}^2 = \sigma \cdot \frac{1.25 \text{ V}}{0.01 \text{ cm}}$$

$$0.08 = (1.6 \times 10^{-19}) (1.207 \times 10^{14}) \times \mu_n$$

$$\Rightarrow \mu_n = 4143 \text{ cm}^2/\text{Vsec}$$

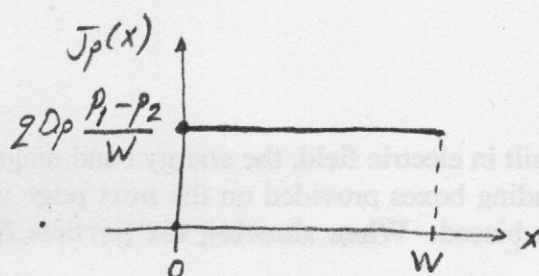
- c.) (4 points) Assume that the steady-state hole density in a semiconductor decreases linearly with increasing x as shown below. Find the expression for the hole current density, $J_p(x)$, in terms of W , P_1 , P_2 and other necessary parameters in the region $0 < x < W$. Sketch $J_p(x)$. Electric field is zero.



Answer: Since $\vec{E} = 0$, we have diffusion component;

$$J_p(x) = q D_p \left(- \frac{\partial p(x)}{\partial x} \right)$$

$$= q D_p \frac{P_1 - P_2}{W} \quad ; \text{ flow is to the +ve } x \text{ direction.}$$



- d.) (6 points) Now, assume that an electric field is present in the semiconductor. Find an expression for the field, $E(x)$, that must exist if there is **no net hole current** associated with the distribution shown above. Determine an expression for $E(x)$ in terms of temperature, P_1 , P_2 and other necessary parameters.

Answer: We have both drift and diffusion components. Then total current density is;

$$J_p(x) = q \mu_p p E + q D_p \frac{P_1 - P_2}{W} \quad \text{In order to set this to zero;}$$

$$E(x) = - \frac{D_p (P_1 - P_2)}{\mu_p p(x) W} \quad \text{where } D_p = \mu_p \frac{kT}{q} \text{ and } p(x) = P_1 - \frac{P_1 - P_2}{W} x$$

$$= - \frac{kT}{q} \cdot \frac{P_1 - P_2}{p(x) W}$$

Note that -ve sign indicates the $\vec{E}$ field is in the opposite direction of diffusion current flow direction.

Re-organizing yields;

$$E(x) = - \frac{kT}{q} \frac{P_1 - P_2}{P_1(W-x) + P_2 x}$$

Q.4. (20 points) A p-n junction is formed by a p-type Si with $N_A = 5 \times 10^{17} \text{ cm}^{-3}$ and an n-type Si with $N_D = 10^{16} \text{ cm}^{-3}$, at 300°K .

a.) (5 points) Calculate the Fermi level positions with respect to E_i at 300°K in the p-type and n-type regions.

Answer: In the p-type region; $p = N_A$, @ 300°K $n_i = 10^{10} \text{ cm}^{-3}$

$$p = n_i \exp(E_i - E_F)/kT$$

$$(E_i - E_F) = kT \ln \frac{p}{n_i} = 8.62 \times 10^{-5} \times 300 \times \frac{5 \times 10^{17}}{10^{10}}$$

$$= 0.458 \text{ eV}$$

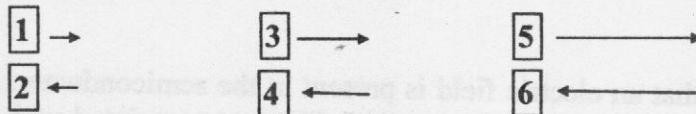
In the n-type region; $n = N_D$, @ 300°K $n_i = 10^{10} \text{ cm}^{-3}$

$$n = n_i \exp(E_F - E_i)/kT$$

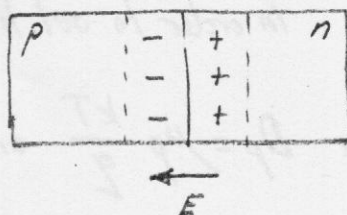
$$(E_F - E_i) = kT \ln \frac{n}{n_i} = 8.62 \times 10^{-5} \times 300 \times \frac{10^{16}}{10^{10}}$$

$$= 0.357 \text{ eV}$$

b.) (15 points) Sketch the electrostatic potential, the built in electric field, the energy band diagram, and the particle flow and the current into the corresponding boxes provided on the next page when the junction is zero biased, forward biased and reverse biased. When showing the particle flow and current select an arrow from the set of arrows:



to represent the direction and the magnitude of flow and write down the corresponding number into the space provided.



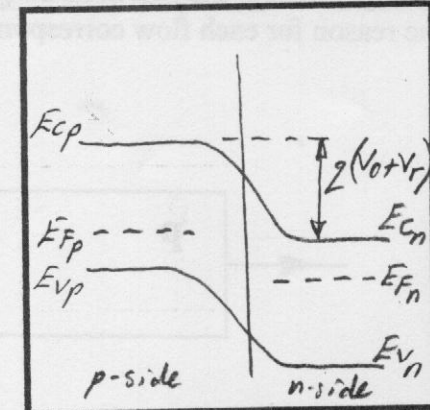
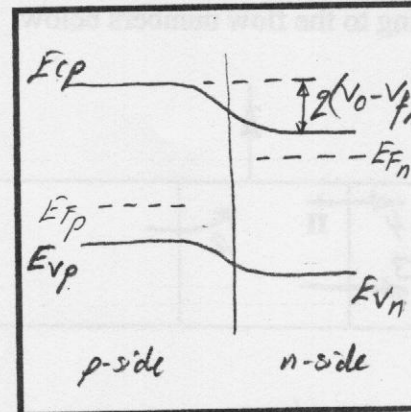
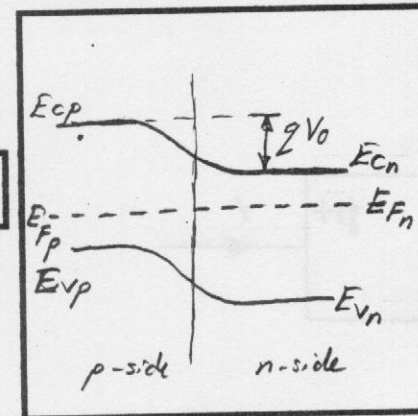
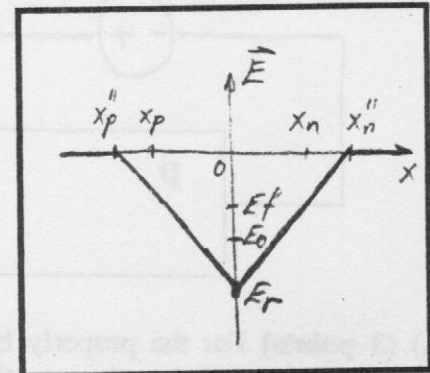
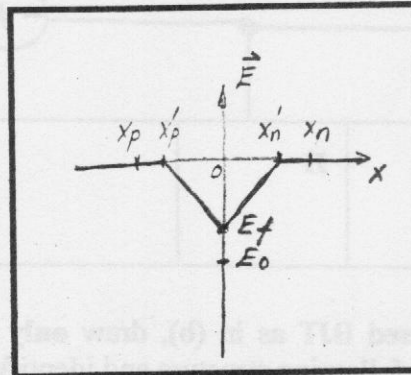
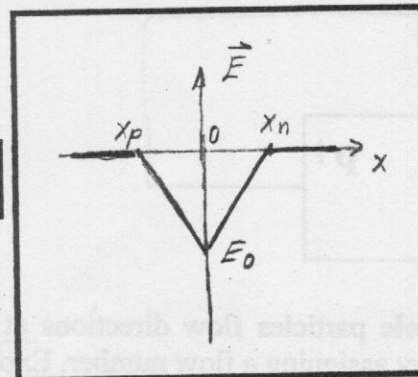
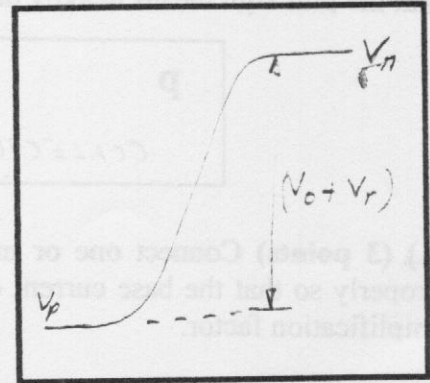
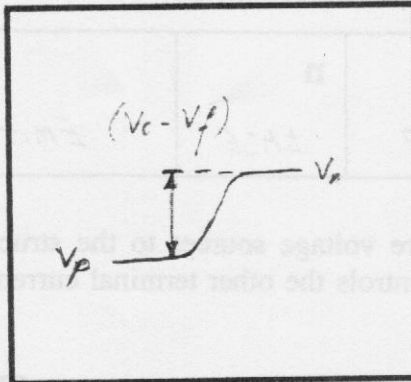
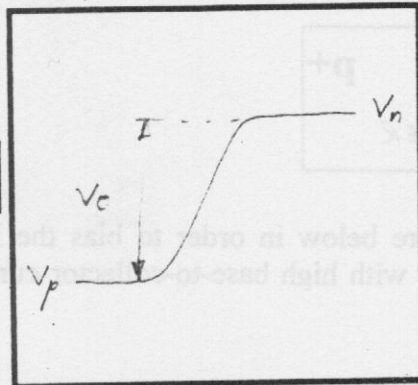
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Zero Bias

Forward Bias

Reverse Bias



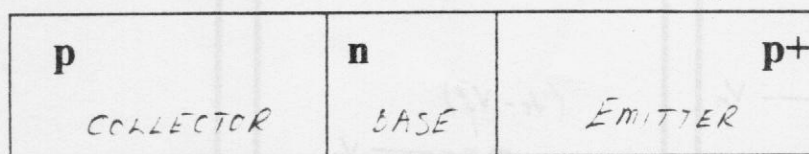
	Particle Flow	Current
Hole Diffusion	3 →	3 →
Hole Drift	4 ←	4 ←
Electron Diffusion	4 ←	3 →
Electron Drift	3 →	4 ←
Electric Field	4 ←	4 ←

	Particle Flow	Current
Hole Diffusion	5 →	5 →
Hole Drift	4 ←	4 ←
Electron Diffusion	6 ←	5 →
Electron Drift	3 →	4 ←
Electric Field	2 ←	2 ←

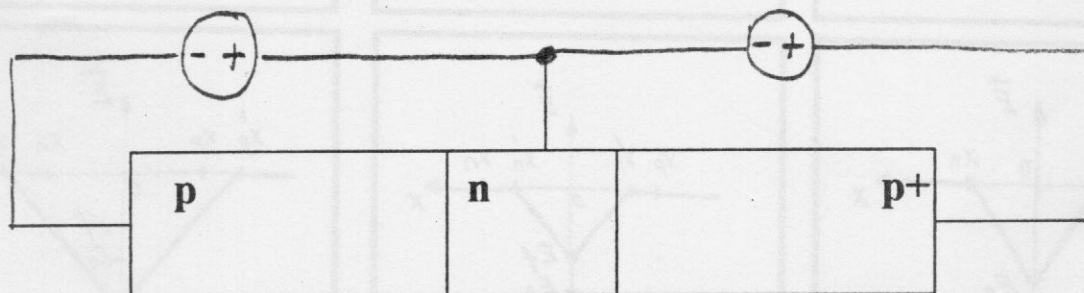
	Particle Flow	Current
Hole Diffusion	1 →	1 →
Hole Drift	4 ←	4 ←
Electron Diffusion	2 ←	1 →
Electron Drift	3 →	4 ←
Electric Field	6 ←	6 ←

Q.5 (20 points)

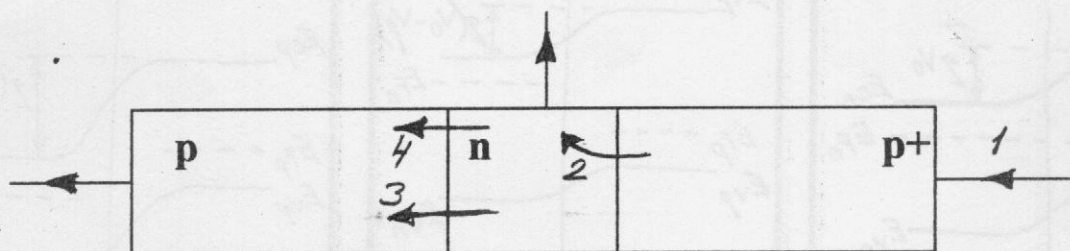
a.) (2 points) Indicate the emitter, collector, and base terminals of the BJT structure shown below. Note that the plus sign means heavily doped semiconductor.



b.) (3 points) Connect one or more voltage sources to the structure below in order to bias the BJT properly so that the base current controls the other terminal currents with high base-to-collector current amplification factor.



c.) (3 points) For the properly biased BJT as in (b), draw **only** hole particles flow directions at the terminals and at the junctions on the following structure and identify by assigning a flow number. Explain the reason for each flow corresponding to the flow numbers below.



Reason for Flow #1 : *Forward biased p^+-n junction.*

Reason for Flow #2 : *Injected holes recombine in the base region.*

Reason for Flow #3 : *Remaining holes reaching the p-type region (collector)*

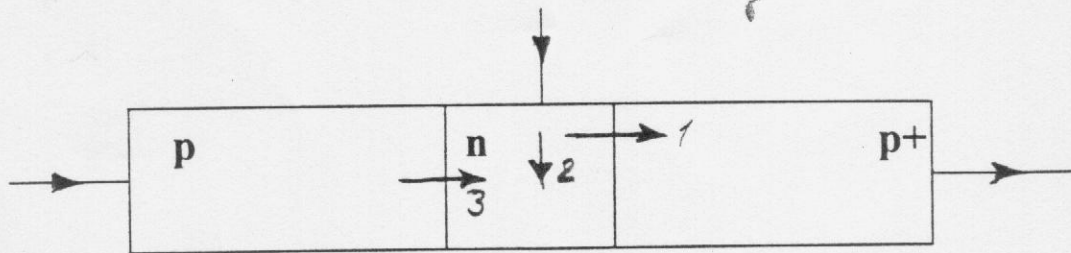
Reason for Flow #4 : *Thermally generated holes resulting reverse saturation current.*

Reason for Flow #5 :

Q.5. continues on the next page

Q.5. continues from the previous page

d.) (4 points) Repeat (c) for **only electron** particles on the structure below.



Reason for Flow #1 : *Forward biased p-n junction.*

Reason for Flow #2 : *Electrons supplied for hole recombination.*

Reason for Flow #3 : *Thermally generated electrons resulting reverse saturation current.*

Reason for Flow #4 :

Reason for Flow #5 :

e.) (4 points) If the diffusion length of minority carriers (L_p) is $100\mu\text{m}$, calculate the width of the base region (W_b) in order to have the base transport factor as 0.99. Use $\ln(0.99) = -0.01$, neglect thermally generated EHPs and consider emitter injection efficiency as unity.

Answer:

$$e^{-x/L_p} \Big|_{x=W_b} = 0.99$$

$$\Rightarrow -W_b = 100\mu\text{m} \times \ln(0.99)$$

$$W_b = 1\mu\text{m}$$

f.) (4 points) Emitter current due to electron flow and hole flow is defined as I_{En} and I_{Ep} , respectively. Base current is defined as I_B . Collector current is defined and given as $I_C = 0.99 I_{Ep}$. If $I_{En} = I_{Ep}/100$ is given, calculate the I_C / I_B ratio.

Answer:

$$I_E = I_{En} + I_{Ep}$$

$$I_B = I_{En} + (1 - 0.99) I_{Ep}$$

$$= 0.01 I_{Ep} + 0.01 I_{Ep}$$

$$= 0.02 I_{Ep}$$

$$\Rightarrow \frac{I_C}{I_B} = \frac{0.99 I_{Ep}}{0.02 I_{Ep}} = \frac{99}{2} = 49.5$$