ECE4904 Lecture 7

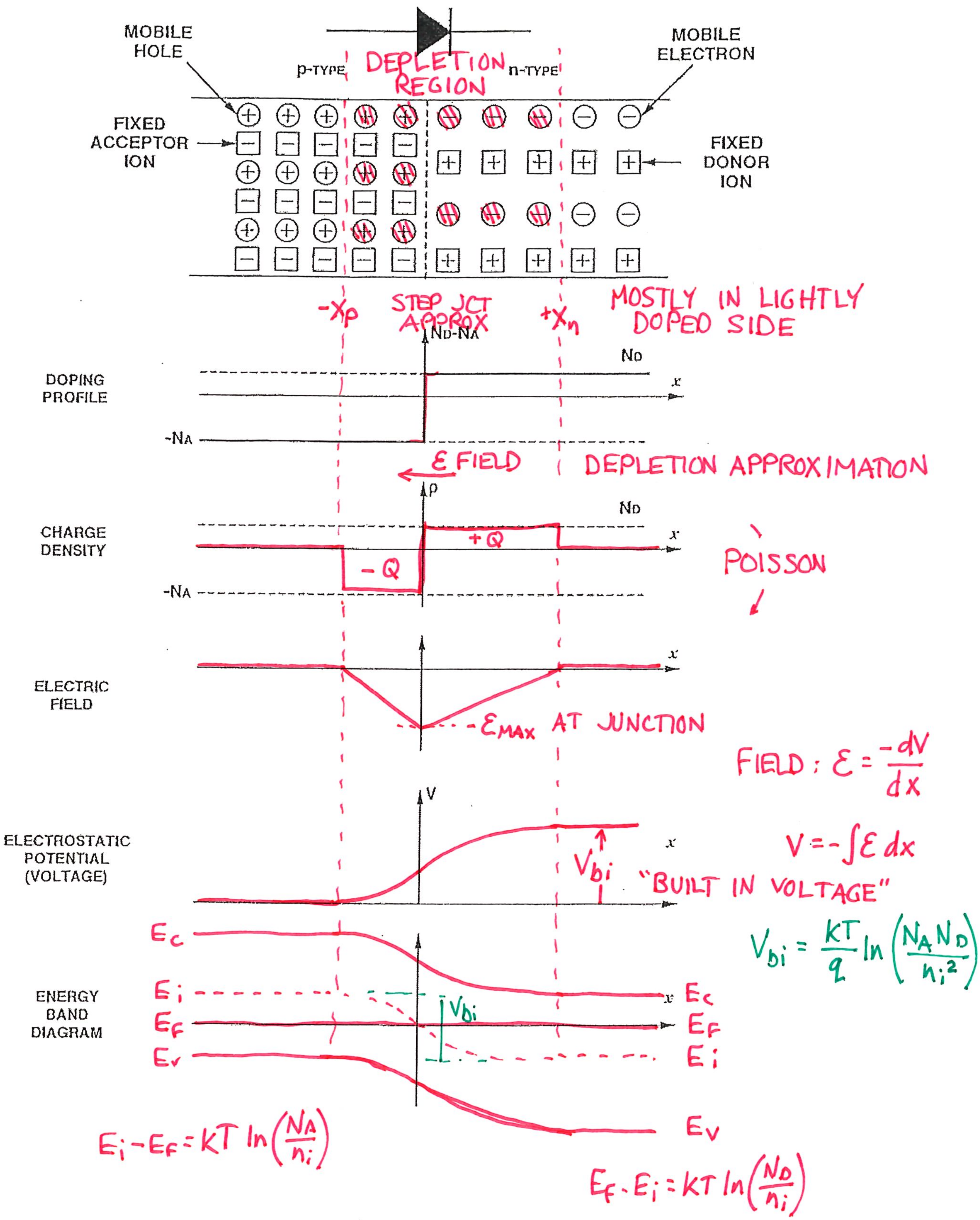
pn junction (5.2)

- Zero bias electrostatics review
- Operating regions:
  - Reverse bias
  - Zero bias
  - Forward bias

Ideal Diode Equation (Ch. 6)

BJT Preview

Handouts
- Ideal Diode Equation Derivation
- Diode Current Component 1-Minute Quiz


MOBILE HOLE
p-TYPE
DEPLETION REGION
n-TYPE
MOBILE ELECTRON
FIXED ACCEPTOR ION
FIXED DONOR ION
-Xp
STEP JCT APPROX
+Xn
MOSTLY IN LIGHTLY DOPED SIDE
DOPING PROFILE
ND-NA
ND
-NA
x
ε FIELD
DEPLETION APPROXIMATION
CHARGE DENSITY
ρ
ND
-Q
+Q
-NA
POISSON
ELECTRIC FIELD
-εMAX AT JUNCTION
FIELD : ε = -dV/dx
ELECTROSTATIC POTENTIAL (VOLTAGE)
V
V = -∫ε dx
Vbi
"BUILT IN VOLTAGE"
Vbi = (kT/q) ln(NA ND / ni²)
ENERGY BAND DIAGRAM
Ec
Ei
EF
Ev
Vbi
Ei - EF = kT ln(NA/ni)
EF - Ei = kT ln(ND/ni)

MORE HEAVILY DOPED SIDE: MORE CONTRIBUTION TO TOTAL CURRENT

$$I = qA\underbrace{\left[\overbrace{\frac{D_N}{L_N}\frac{n_i^2}{N_A}}^{e^-} + \overbrace{\frac{D_p}{L_p}\frac{n_i^2}{N_D}}^{\text{HOLES}}\right]}_{I_S}\left(\overbrace{e^{qV_A/kT}}^{\text{DIFF}}\overbrace{-1}^{\text{DRIFT}}\right)$$

$\frac{kT}{q} = 25.9\,mV$ @ $T = 300K$

"SCALE CURRENT"

PROPORTIONAL TO AREA A

BIGGER AREA → MORE I FOR APPLIED VA

$I_S \propto n_i^2$: VERY T DEPENDENT!

A ↓I

I↓ + V_A −

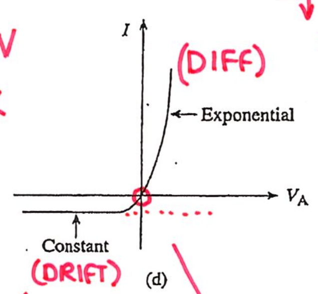


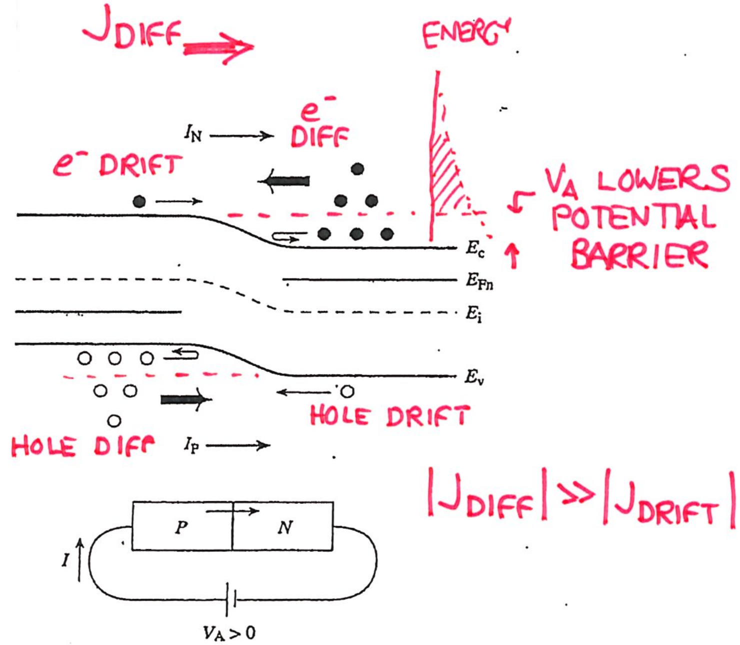
Figure 6.1

REVERSE BIAS

ZERO BIAS

— FORWARD BIAS →

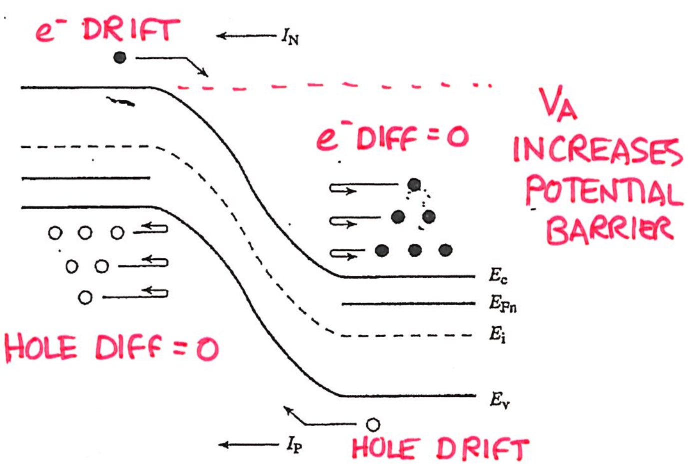
J_{DIFF} ⇒



(b) Forward bias ($V_A > 0$)

$|J_{DIFF}| \gg |J_{DRIFT}|$

Figure 6.1 *pn* junction energy band diagram, carrier distributions, and carrier activity in the near vicinity of the depletion region under (a) equilibrium ($V_A = 0$), (b) forward bias, and (c) reverse bias conditions. (d) Deduced form of the *I–V* characteristic.



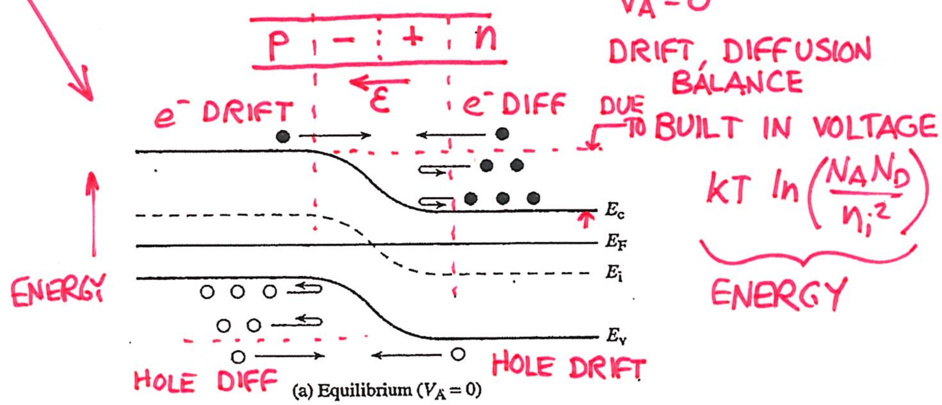
(c) Reverse bias ($V_A < 0$)

J_{DIFF} TURNED OFF

★ REV BIAS: DRIFT CURRENT

$V_A = 0$

DRIFT, DIFFUSION BALANCE



(a) Equilibrium ($V_A = 0$)

$$\underbrace{kT \ln\left(\frac{N_A N_D}{n_i^2}\right)}_{\text{ENERGY}}$$

ECE4904 IDEAL DIODE EQUATION DERIVATION (p. 1)

Minority carrier diffusion equations (valid in quasineutral region where E field ≈0)

e⁻ ON p SIDE

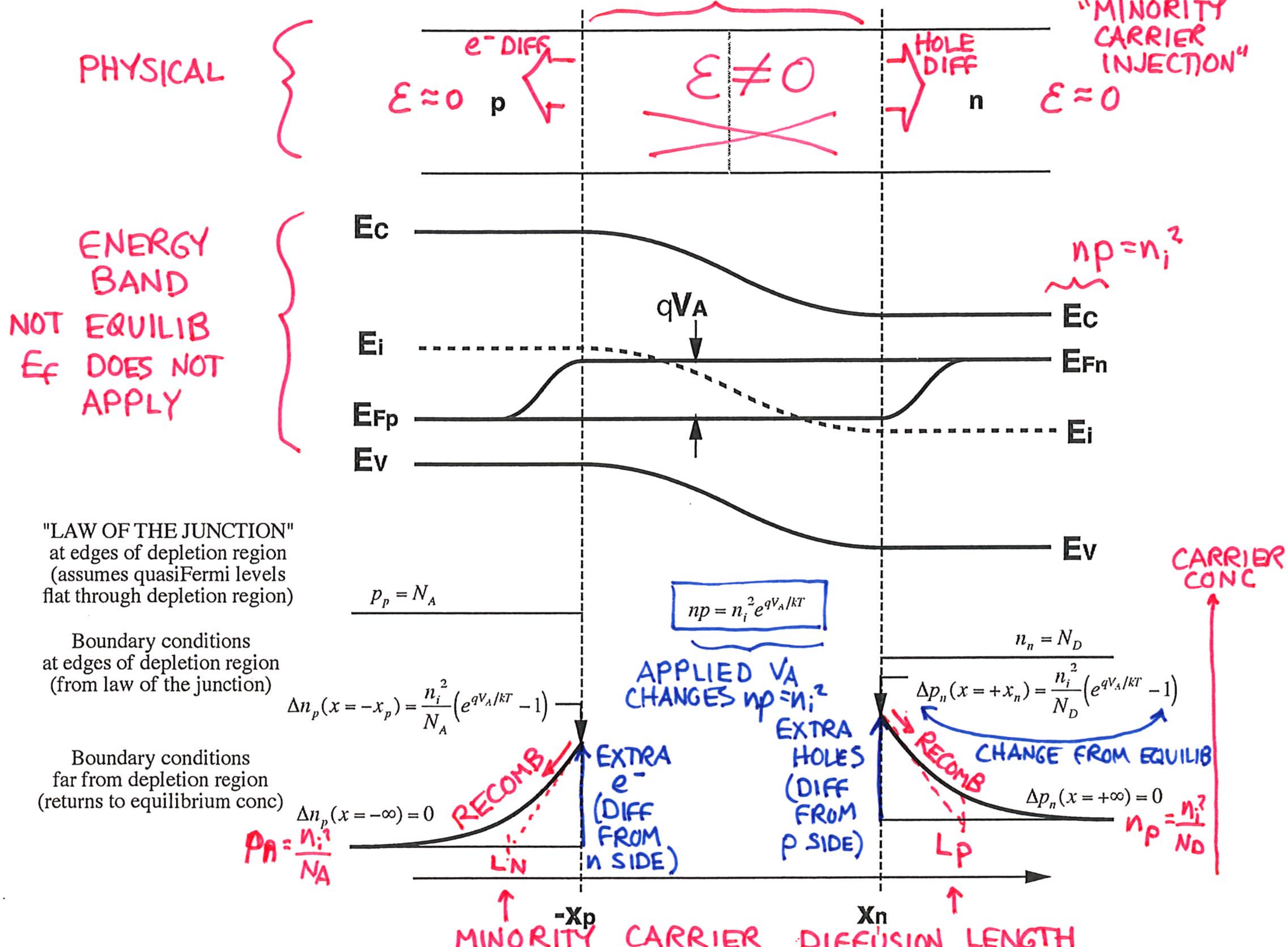
$$\frac{\partial \Delta n_p}{\partial t} = D_N \frac{\partial^2 \Delta n_p}{\partial x^2} - \frac{\Delta n_p}{\tau_N} \quad \cancel{G_L} \rightarrow 0$$

HOLES ON n SIDE

$$\frac{\partial \Delta p_n}{\partial t} = D_P \frac{\partial^2 \Delta p_n}{\partial x^2} - \frac{\Delta p_n}{\tau_P} \quad \cancel{G_L} \rightarrow 0$$

Steady state (DC voltage, current: all d/dt = 0)

$$0 = D_N \frac{d^2 \Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_N} \qquad 0 = D_P \frac{d^2 \Delta p_n}{dx^2} - \frac{\Delta p_n}{\tau_P}$$



"LAW OF THE JUNCTION" at edges of depletion region (assumes quasiFermi levels flat through depletion region)

Boundary conditions at edges of depletion region (from law of the junction)

Boundary conditions far from depletion region (returns to equilibrium conc)

Solutions to differential equation subject to boundary conditions

$$\Delta n_p(x=-x_p) = \frac{n_i^2}{N_A}\left(e^{qV_A/kT}-1\right)e^{(x+x_p)/L_N} \qquad \Delta p_n(x=+x_n) = \frac{n_i^2}{N_D}\left(e^{qV_A/kT}-1\right)e^{-(x-x_n)/L_P}$$

Current density equation (FOR DIFF CURRENT)

$$J_N = qD_N \frac{d\Delta n_p}{dx} \qquad J_P = -qD_P \frac{d\Delta p_n}{dx}$$

Plug differential equation solution into current density equation

$$J_N = q\frac{D_N}{L_N}\frac{n_i^2}{N_A}\left(e^{qV_A/kT}-1\right)e^{(x+x_p)/L_N} \quad (x \le -x_p) \qquad J_P = q\frac{D_P}{L_P}\frac{n_i^2}{N_D}\left(e^{qV_A/kT}-1\right)e^{-(x-x_n)/L_P} \quad (x \ge +x_n)$$

ON p SIDE e⁻ ←

→ ON n SIDE HOLES

$$\frac{D}{\mu} = \frac{kT}{q} \qquad D = \mu\frac{kT}{q}$$

ECE4904 IDEAL DIODE EQUATION DERIVATION (p. 2)

Current density equation

$$J_N = qD_N\frac{d\Delta n_p}{dx} \qquad\qquad J_P = -qD_P\frac{d\Delta p_n}{dx}$$

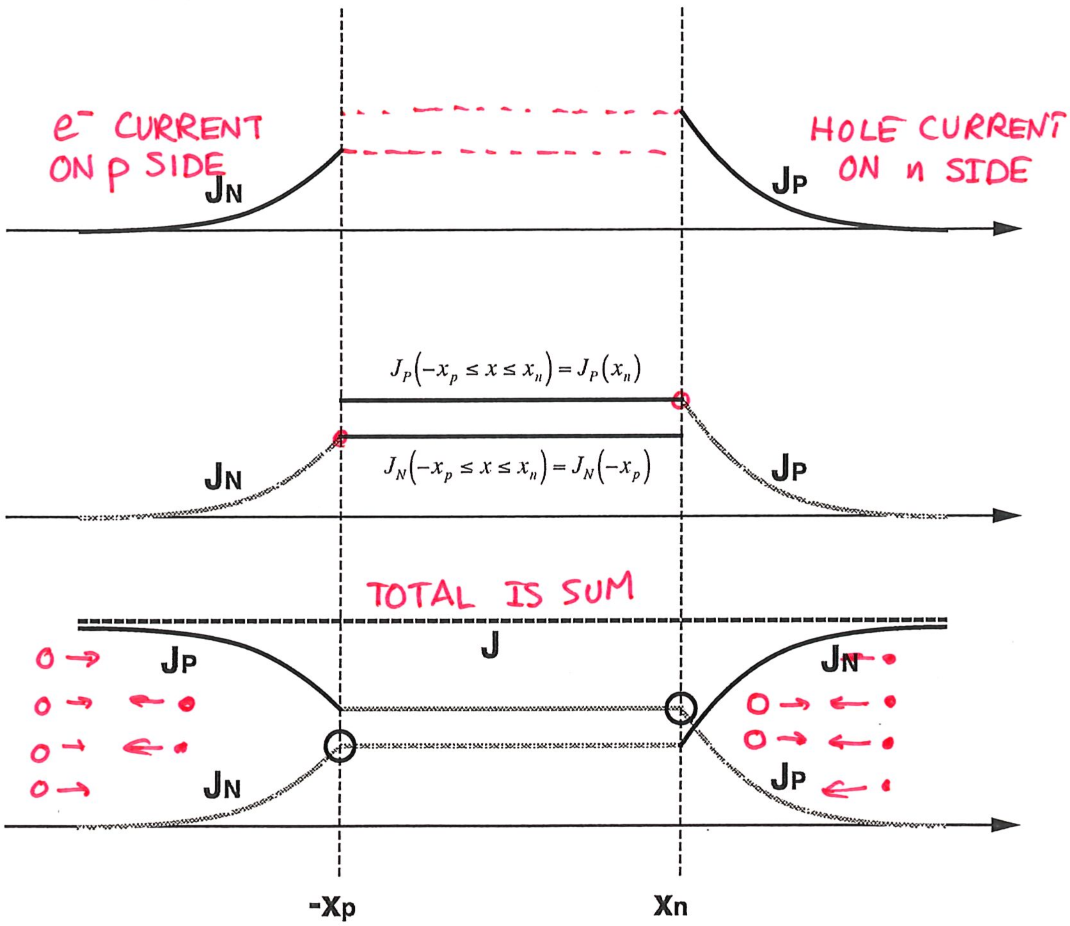
$$J_N = q\frac{D_N}{L_N}\frac{n_i^2}{N_A}\left(e^{qV_A/kT}-1\right)e^{(x+x_p)/L_N} \quad (x \le -x_p) \qquad J_P = q\frac{D_P}{L_P}\frac{n_i^2}{N_D}\left(e^{qV_A/kT}-1\right)e^{-(x-x_n)/L_P} \quad (x \ge +x_n)$$

Plug differential equation solution into current density equation

Assume no R-G in depletion region

Steady state: total J constant throughout

J given by sum of hole. electron components at edges of depletion region



Evaluate current density expressions at edges of depletion region

$$J_N(-x_p) = q\frac{D_N}{L_N}\frac{n_i^2}{N_A}\left(e^{qV_A/kT}-1\right) \qquad\qquad J_P(x_n) = q\frac{D_P}{L_P}\frac{n_i^2}{N_D}\left(e^{qV_A/kT}-1\right)$$

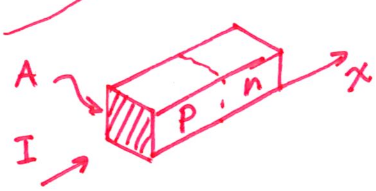
Total current density

$$J = q\left[\frac{D_N}{L_N}\frac{n_i^2}{N_A} + \frac{D_P}{L_P}\frac{n_i^2}{N_D}\right]\left(e^{qV_A/kT}-1\right)$$

Total current I=JA Current density x junction area A

$$\boxed{I = qA\left[\underbrace{\frac{D_N}{L_N}\frac{n_i^2}{N_A}}_{e^- \text{ ON } p \text{ SIDE}} + \underbrace{\frac{D_P}{L_P}\frac{n_i^2}{N_D}}_{\text{HOLES ON } n \text{ SIDE}}\right]\underbrace{\left(e^{qV_A/kT}-1\right)}_{\text{FROM LAW OF THE JUNCTION}}}$$

JUNCTION AREA



ECE4904 p-n Junction Diode Current Component "One Minute Quiz"

	HOLE	e^-
DRIFT	✓	✓
DIFF	✓	✓

Arrows in the diagram below indicate carrier motion

a) Does this represent forward bias, ~~zero bias (equilibrium)~~, or reverse bias?

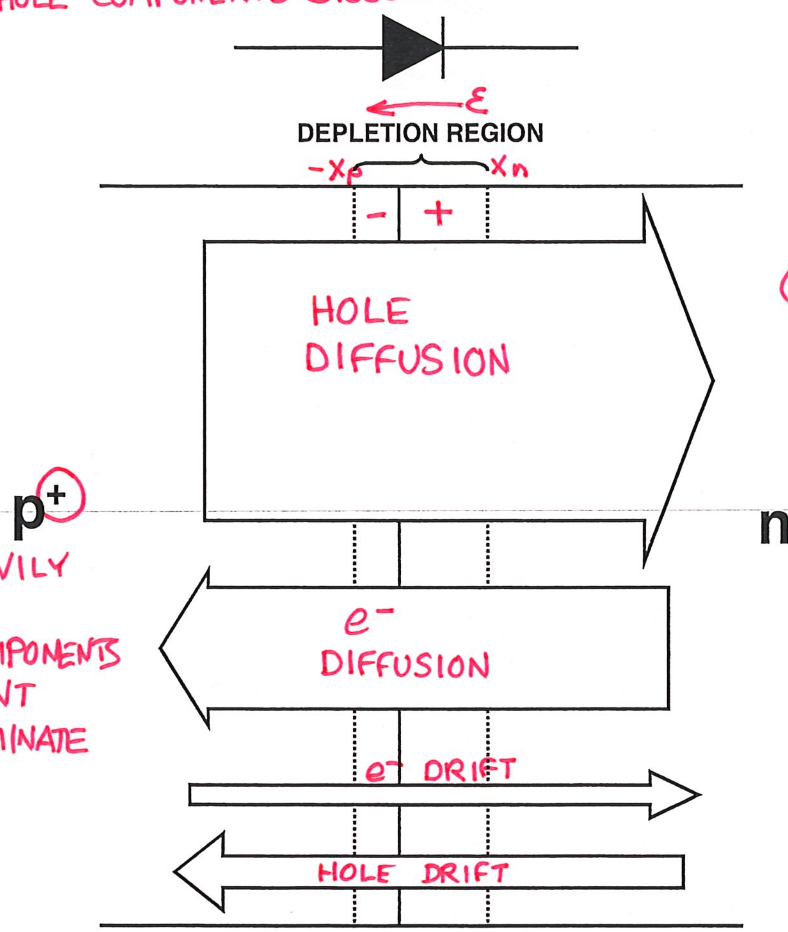
DIFFUSION DOMINATES   ARROW TOTAL $\neq 0$ DRIFT

b) For each arrow, identify whether it corresponds to hole or e^- motion

c) For each arrow, identify whether it corresponds to drift or diffusion

d) Find at least 3 characteristics that indicate $N_A >> N_D$

1. WIDTH OF DEPLETION REGION $x_n > x_p$
2. p^+ SUPERSCRIPT
3. HOLE COMPONENTS BIGGER



HOLE DIFF OR e^- DRIFT

p MORE HEAVILY DOPED

MORE HEAVILY DOPED

⇒ HOLE COMPONENTS OF CURRENT WILL DOMINATE

e) In the space below indicate the current density components corresponding to each carrier motion arrow

$\Rightarrow$ $J_p|_{diff}$

$\Rightarrow$ $J_n|_{diff}$

} DIFFUSION DOMINATES } FWD BIAS

$\leftarrow$ $J_p|_{drift}$

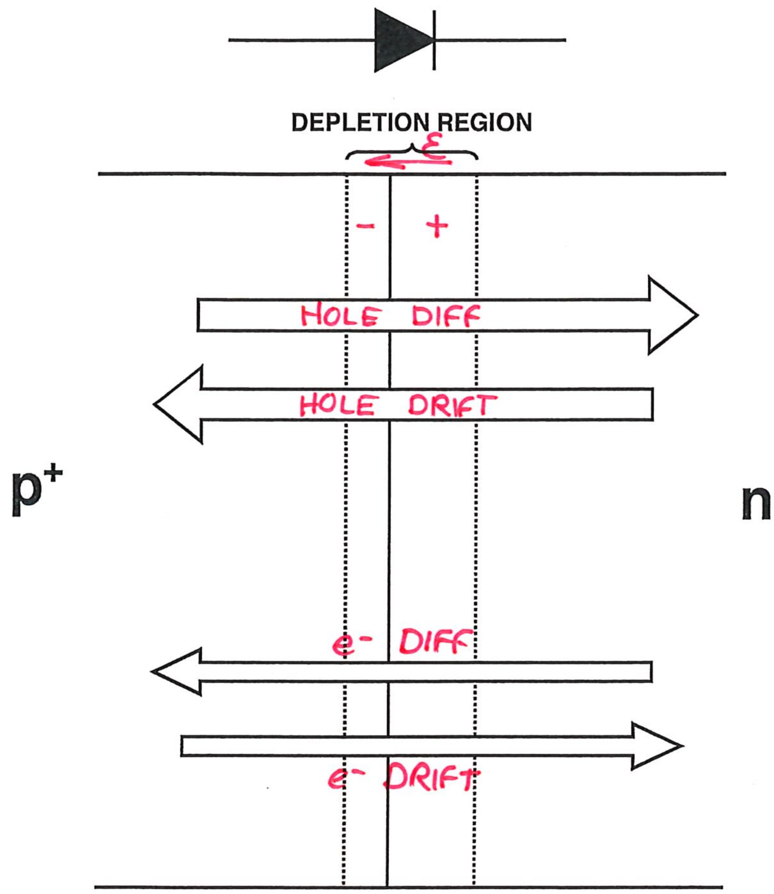
$\leftarrow$ $J_n|_{drift}$

Arrows in the diagram below indicate carrier motion

a) Does this represent forward bias, zero bias (equilibrium), or reverse bias?

ALL CURRENTS TOTAL ZERO

b) For each arrow, identify whether it corresponds to hole or e⁻ motion
c) For each arrow, identify whether it corresponds to drift or diffusion



HOLES

BIGGER ARROWS SINCE p⁺ n MORE HEAVILY DOPED

e⁻

d) In the space below indicate the current density components corresponding to each carrier motion arrow

$J_p|_{diff} \longrightarrow$

$J_p|_{drift} \longleftarrow$

EQUAL AND OPPOSITE

$J_n|_{diff} \longrightarrow$

$J_n|_{drift} \longleftarrow$