Quantitative Model of Unilluminated Diode – part II

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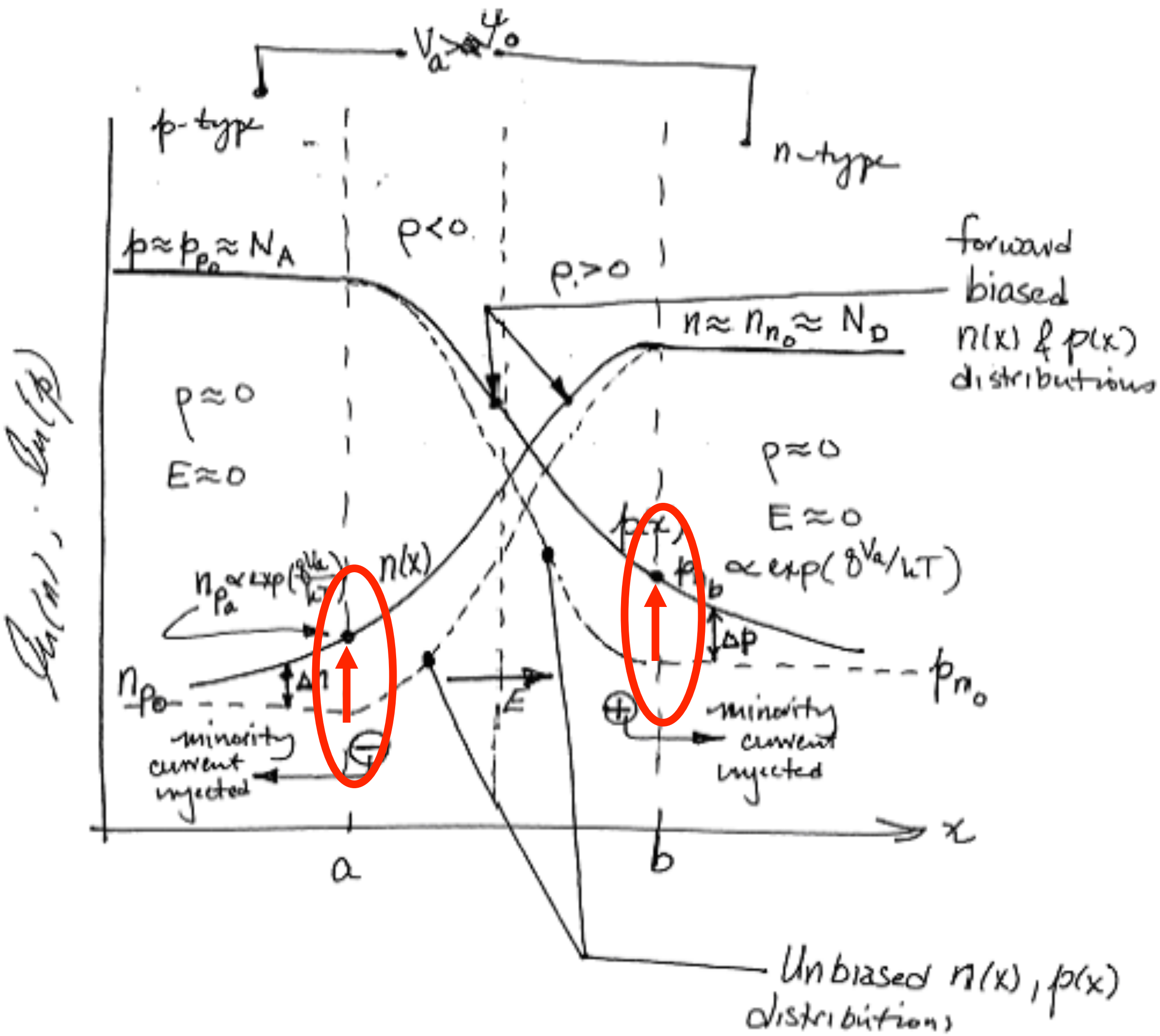
UC San Diego MAE 119

Lecture Notes

Minority Carrier Density at edge of quasineutral region increases **EXPONENTIALLY** forward bias



$$p_{n_b} = p_{n_0} \exp\left[\frac{qV_a}{kT}\right]$$

$$n_{p_a} = n_{p_0} \exp\left[\frac{qV_a}{kT}\right]$$

What happens to these charges once they get into the quasi-neutral region?

- Depletion Region Is Surrounded by two QUASINEUTRAL Regions where E=0
- **Current Transport Occurs Via Diffusion in This Region**

$$J_e \sim qD_e \frac{dn}{dx}$$

$$J_h \sim -qD_h \frac{dp}{dx}$$

Summary so far:

- Can divide p-n junction diode into two regions
  - Quasineutral & Depletion Regions
- Minority Carrier Concentration at Depletion Edge Depends Exponentially on Ext. Voltage
- In Quasi-neutral Region Charge Carriers Move by Diffusion
- Solution to Diffusion Eqn ➔ Charge & Current in Quasi-neut. regions

Consider n-side of diode:

Current Diffusion:

$$J_h \sim -qD_h \frac{dp}{dx}$$

Hole Conservation Law (similar to Fluid continuity eqn)

$$\frac{1}{q}\frac{dJ_h}{dx} = -(U - G)$$

HOW TO TREAT U AND G
TERMS?

Basic Equations of Semiconductors

- We Need Expressions for U and for G
  - G ~ Generation Rate/Unit Volume of e/hole pairs via photon adsorption
  - U ~ Loss Rate/Unit Volume of e/hole pairs via relevant mechanisms
- ➔ Must Examine Photon Adsorption Process & e/hole Loss Processes…

Basics of Solar PV Cells

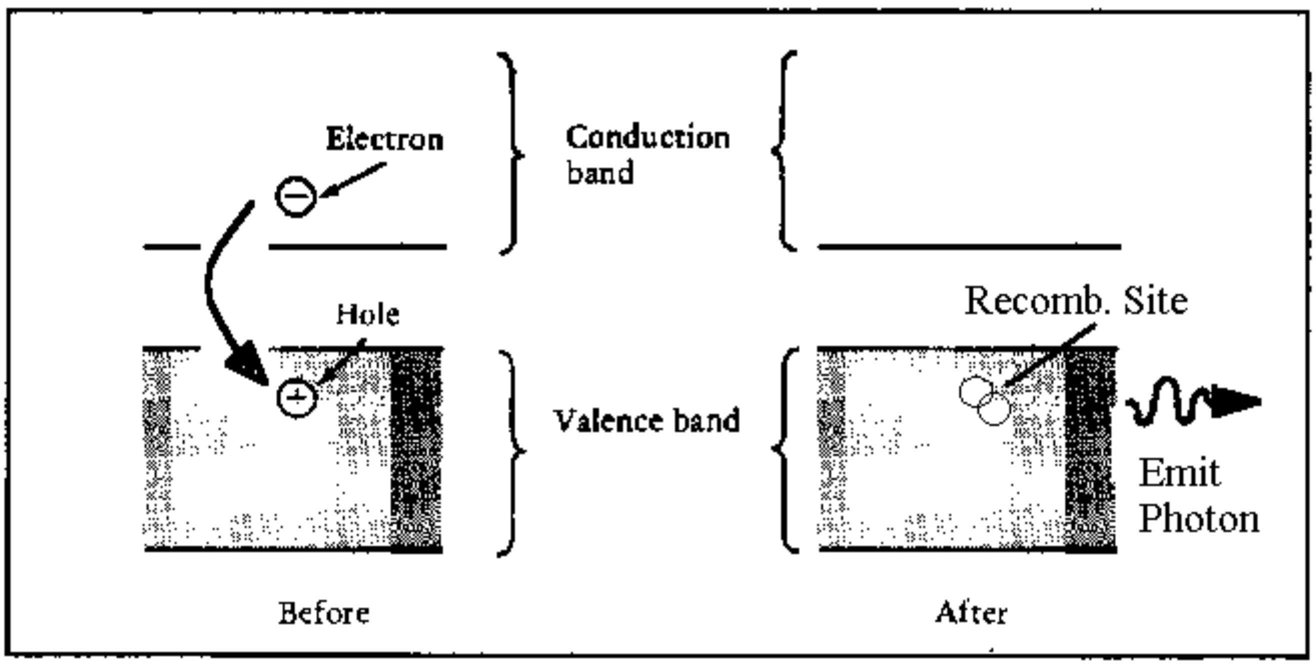
- Key Concepts
  - Photon Energy Spectrum
  - Charge Carrier Generation Via Photon Absorption
  - ***Charge Carrier Loss Mechanisms***
  - Un-illuminated p-n junction diode
  - Illuminated p-n junction diode: The Solar PV Cell
  - Solar PV Cell's as an Electricity Source

Charge Carrier Loss Mechanisms

- Radiative Recombination
- "Auger" Recombination
- Recombination at Traps
  - Bulk Defects & Impurities
  - Crystal Surfaces/Boundaries

I: Radiative Recombination

REVERSE of Photon Adsorption Process:



I: Radiative Recombination

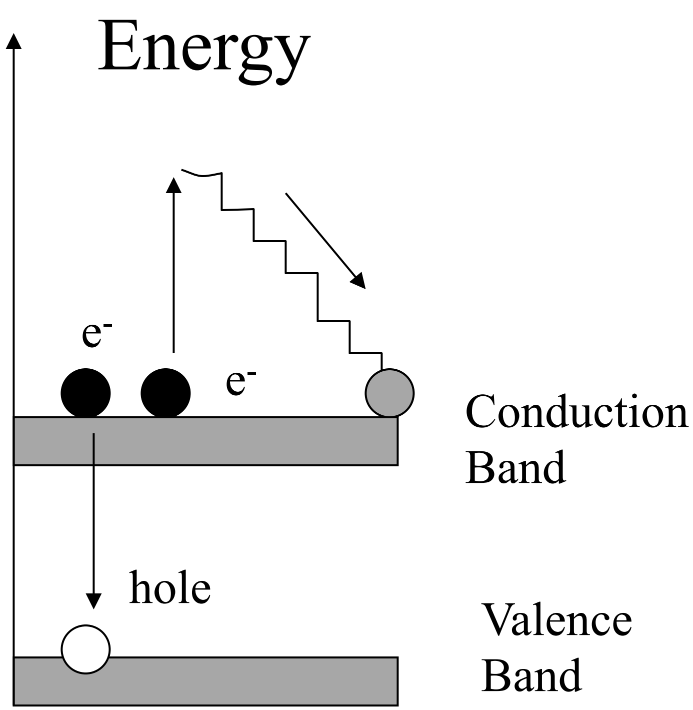
What is the Rate, U_R, of this process (#/unit volume/unit time) ?

A. In Thermal Equilibrium U_R=0 (by definition)
B. Rate Proportional to e-density (n) and to Hole density (p)
C. Infer That Away from Equilibrium, Rate Is

$$U_R = B(np - n_i^2)$$

Where B is a rate constant that depends upon the material (for Silicon B~2×10^{-15} cm^3/sec)

II: Auger Recombination



- Energetic Electron Recombines with Hole
- MUST Get Rid of Excess Energy
  - Transfers to Second Electron
- This Second Electron "Cascades" Back to Lower Energy
- Energy is Transferred to Material (as HEAT)

II: Auger Recombination

- Electron Auger Lifetime: $\frac{1}{\tau} = Cnp + Dn^2$
- Hole Auger Lifetime $\frac{1}{\tau} = Cnp + Dp^2$
- $U=Dn/t_e =Dp/t_h$
- Usually An Important Loss Process

III. Defect & Crystalline Surface Recombination

- Defects Can Induce e/hole recombination
- Defects Consist of
  - Unwanted Impurity Atoms
  - Bulk Crystal Defects (I.e. missing atoms, missing rows, etc…)
- Surfaces Can Also Induce e/hole recombination
  - Adjacent microcrystal surfaces
  - Solid-Air Interface

III. Defect & Crystalline Surface Recombination

- Implication
  - ➔ WANT TO KEEP UNWANTED IMPURITIES OUT OF PV CELL
  - ➔ WANT TO MINIMIZE NUMBER OF MICROCRYSTALS (I.E. MAKE OUT OF A SINGLE CRYSTAL)

BOTH EFFECTS IMPACT MANUFACTURING TECHNIQUES AND COSTS

Model these losses w/ **Carrier Lifetime**

Carrier lifetimes: τ_e & τ_h

$$\tau_e = \frac{n - n_o}{U} = \frac{\Delta n}{U}; \quad n_o \sim \text{equilibrium value of } n$$

$$\tau_h = \frac{p - p_o}{U} = \frac{\Delta p}{U}; \quad p_o \sim \text{equilibrium value of } p$$

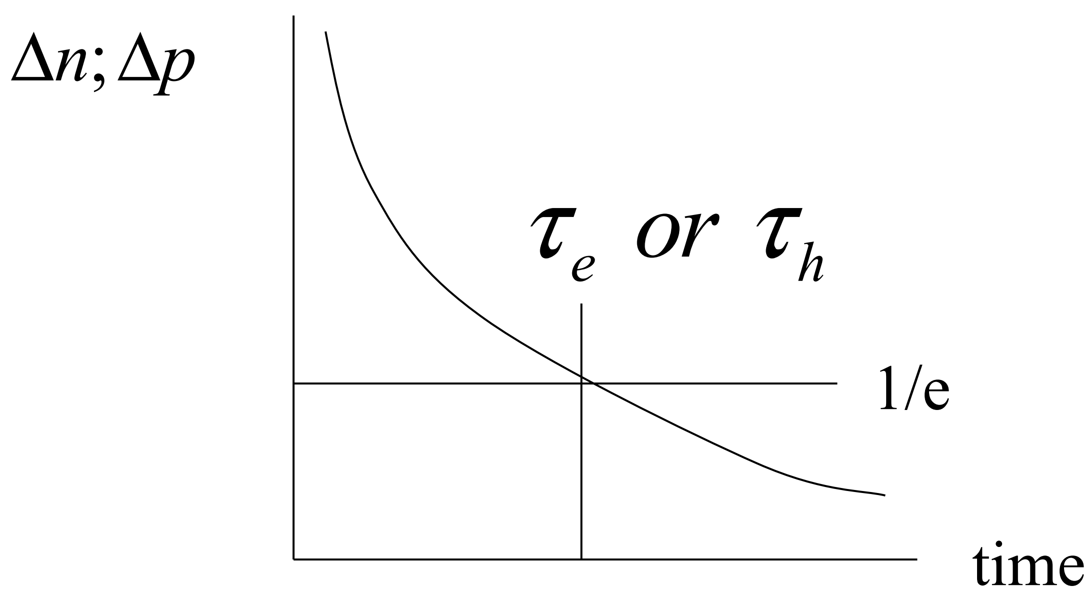
For Radiation Recombination with $\Delta n = \Delta p$

$$\tau = \frac{n_o p_o}{B n_i^2 (n_o + p_o)} \qquad B \sim 2\times 10^{-15} \frac{cm^3}{\sec}$$

Carrier Lifetime Concept (cont'd)

Carrier lifetimes, : $\tau_e \ \& \ \tau_h$

Non-equilibrium Carrier Density
Can Then Decay:



Consider n-side of diode:

Minority Carrier (holes) Diffusion:

$$J_h \sim -qD_h \frac{dp}{dx}$$

Hole Conservation Law (similar to Fluid continuity eqn)

$$\frac{1}{q}\frac{dJ_h}{dx} = -(U - G)$$

But we had $U=(p_n - p_0)/\tau_h = \Delta p/\tau_h$

➔ FIND A DIFFUSION EQUATION W/ SOURCE TERM:

$$\frac{d^2 \Delta p}{dx^2} = \frac{\Delta p}{L_h^2} - \frac{G}{D_h} \qquad L_h = \sqrt{D_h \tau_h}$$

Basics of Solar PV Cells

- Key Concepts
  - Photon Energy Spectrum
  - Charge Carrier Generation Via Photon Absorption
  - Charge Carrier Loss Mechanisms
  - ***Un-illuminated p-n junction diode***
  - Illuminated p-n junction diode: The Solar PV Cell
  - Solar PV Cell's as an Electricity Source

Un-illuminated ("DARK") p-n Diode Response

Set G=0; Use $\frac{\partial^2 p_{n_0}}{\partial x^2} = 0$

Find the Equation $\frac{d^2 \Delta p}{dx^2} = \frac{\Delta p}{L_h^2}; \quad L_h^2 \equiv D_h \tau_h$

Gen. Soln: $\Delta p = Ae^{x/L_n} + Be^{-x/L_h}$

B.C.'s:

At Junction/n-type border ("x=0") $p_{n_b} = p_{n_0} e^{qV/kT}$

$$p_n > 0 \ \ for \ \ x \rightarrow \infty \Rightarrow A = 0$$

Un-illuminated ("DARK") p-n Diode Response

Particular Solutions of Minority Carrier Densities in Quasineutral Regions

$$p_n(x) = p_{n_0} + p_{n_0}[e^{qV/kT} - 1]e^{-x/L_h}$$

$$n_p(x') = n_{p_0} + n_{p_)}[e^{qV/kT} - 1]e^{-x/L_e}$$

Where x, x' are displacements away from junction-quasineutral Region interface…

Distribution of charge carriers under forward bias

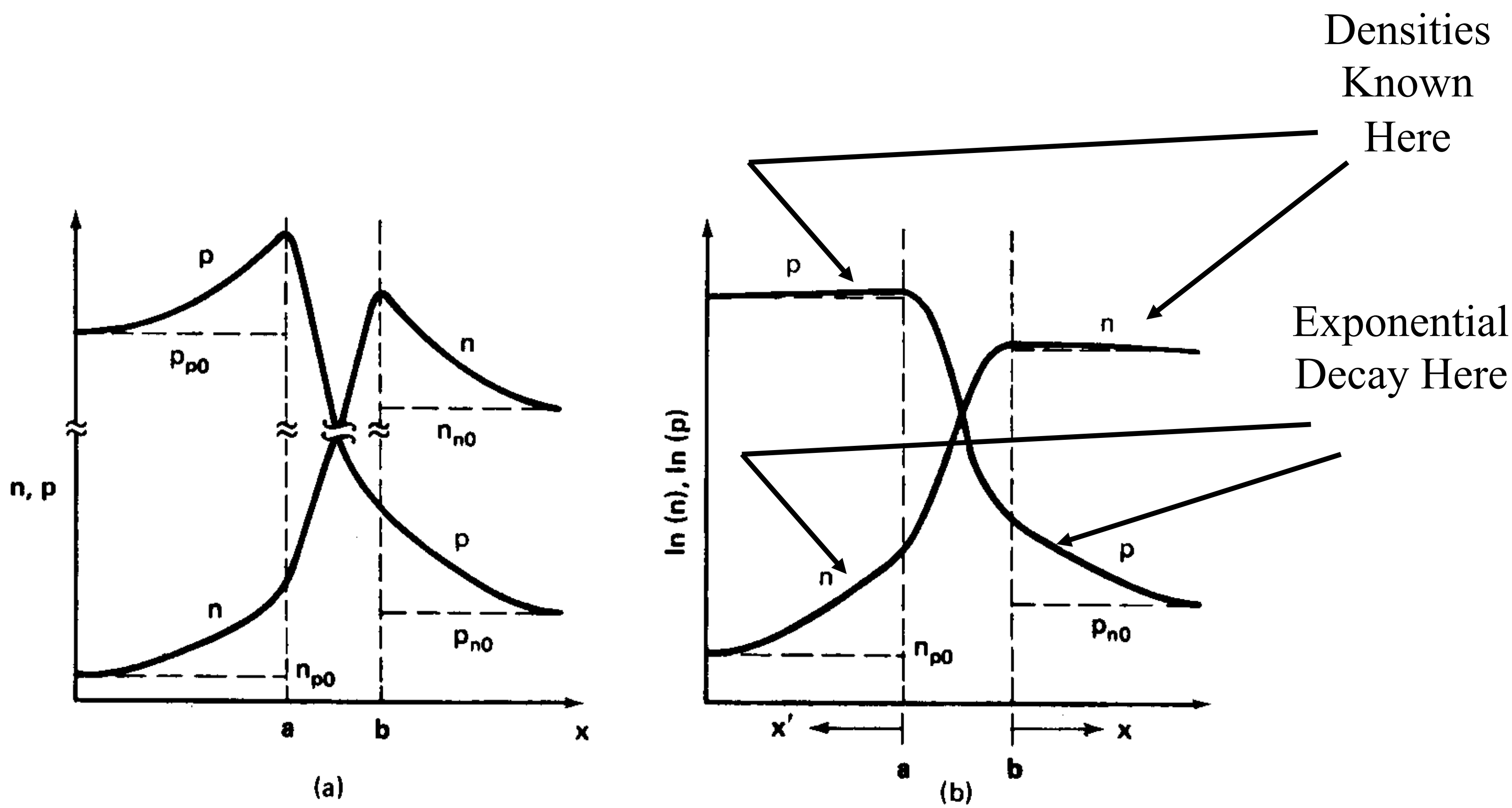


Figure 4.8. (a) Linear plot of the distributions of carriers throughout the *p-n* junction diode under forward bias. (b) Corresponding semilogarithmic plot. Note the differences with respect to majority carriers.

Charge Carrier Distributions Known… Can Find Currents Now:

For Minority Carrier Currents in Quasineutral Region

E.g. on n-type side $J_h(x) = -qD_h \frac{dp}{dx}$

Thus find minority carrier currents:

$$J_h(x) = \frac{qD_h p_{n_0}}{L_h} (e^{qV/kT} - 1) e^{-x/L_h}$$

$$J_e = \frac{qD_e n_{p_0}}{L_e} (e^{qV/kT} - 1) e^{-x'/L_e}$$

Known Current distribution across p-n diode (so far…)

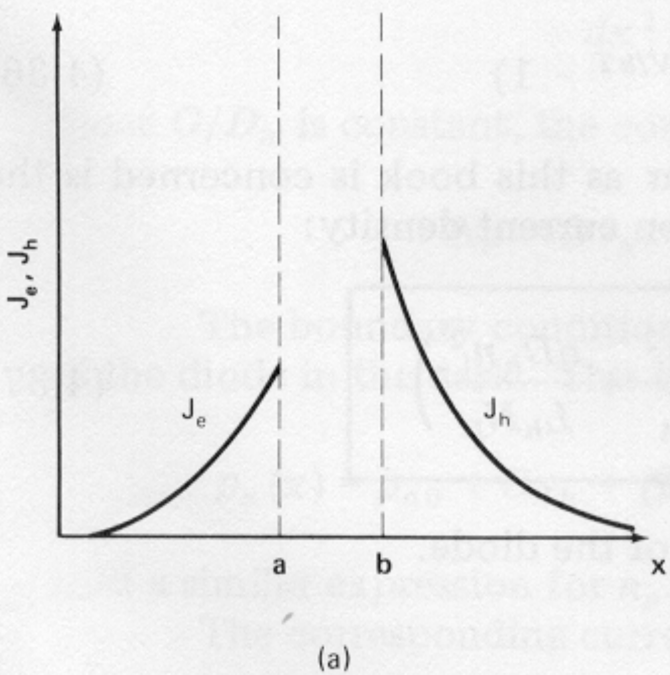


Figure 4.9. (a) Minority-carrier current densities in a *p-n* junction diode corresponding to Fig. 4.8. (b) Distribution of minority, majority, and total current densities in the diode, neglecting recombination in the depletion region.

$$J_h(x) = \frac{qD_h p_{n_0}}{L_h}\left(e^{qV/kT} - 1\right) e^{-x/L_h}$$

$$J_e(x') = \frac{qD_e n_{p_0}}{L_e}\left(e^{qV/kT} - 1\right) e^{-x'/L_e}$$

Need Current Flow in Depletion Region (aka Transition Region or Junction)

Current continuity equation gives

$$-\frac{1}{q}\frac{dJ_h}{dx} = (U - G) = \frac{1}{q}\frac{dJ_e}{dx}$$

Integrate across junction to find change in current:

$$\delta J_e = \left|\delta J_h\right| = q\int_{-W}^{0}(U - G)dx$$

Usually W << L_e, L_h ➔ Change in Current Is Small & Implies…

<u>IF G=0….</u> Current Across Junction is ~Constant & Current Distribution Looks Like:

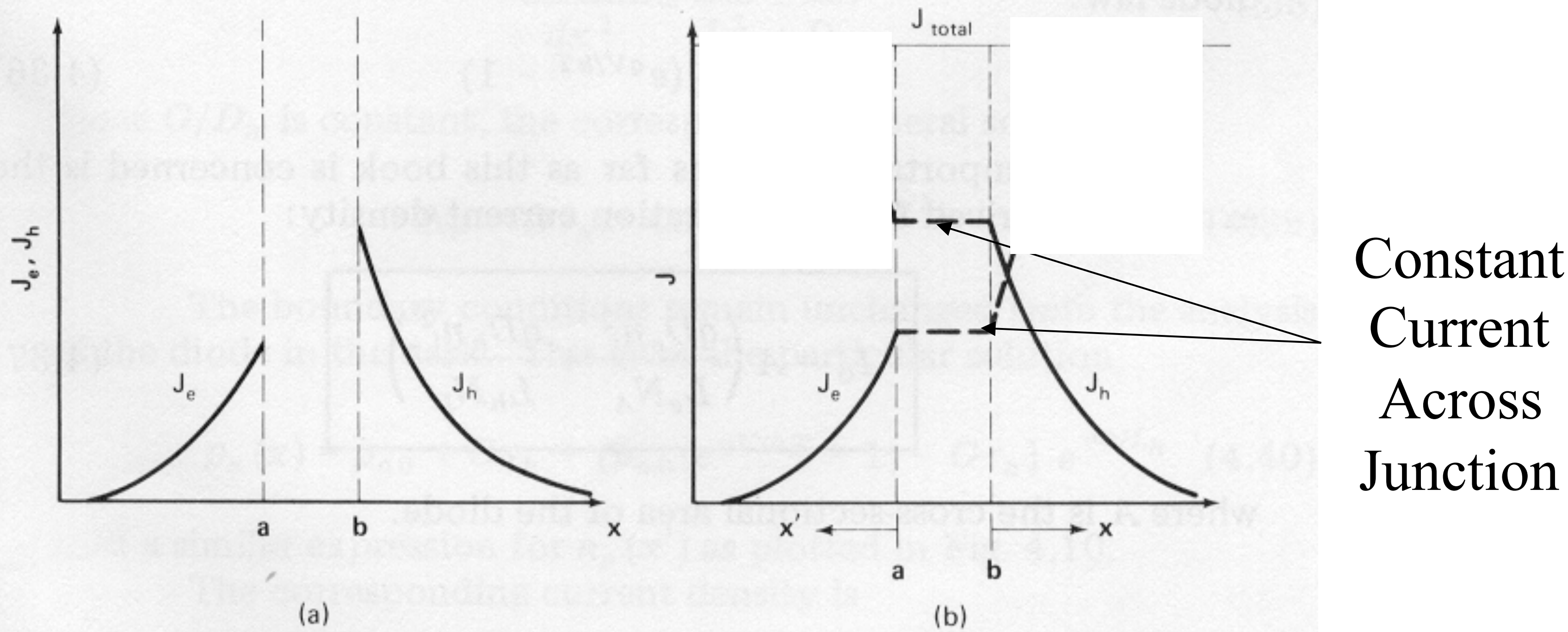


Figure 4.9. (a) Minority-carrier current densities in a *p-n* junction diode corresponding to Fig. 4.8. (b) Distribution of minority, majority, and total current densities in the diode, neglecting recombination in the depletion region.

How to Find Majority Current in Quasineutral Region ?

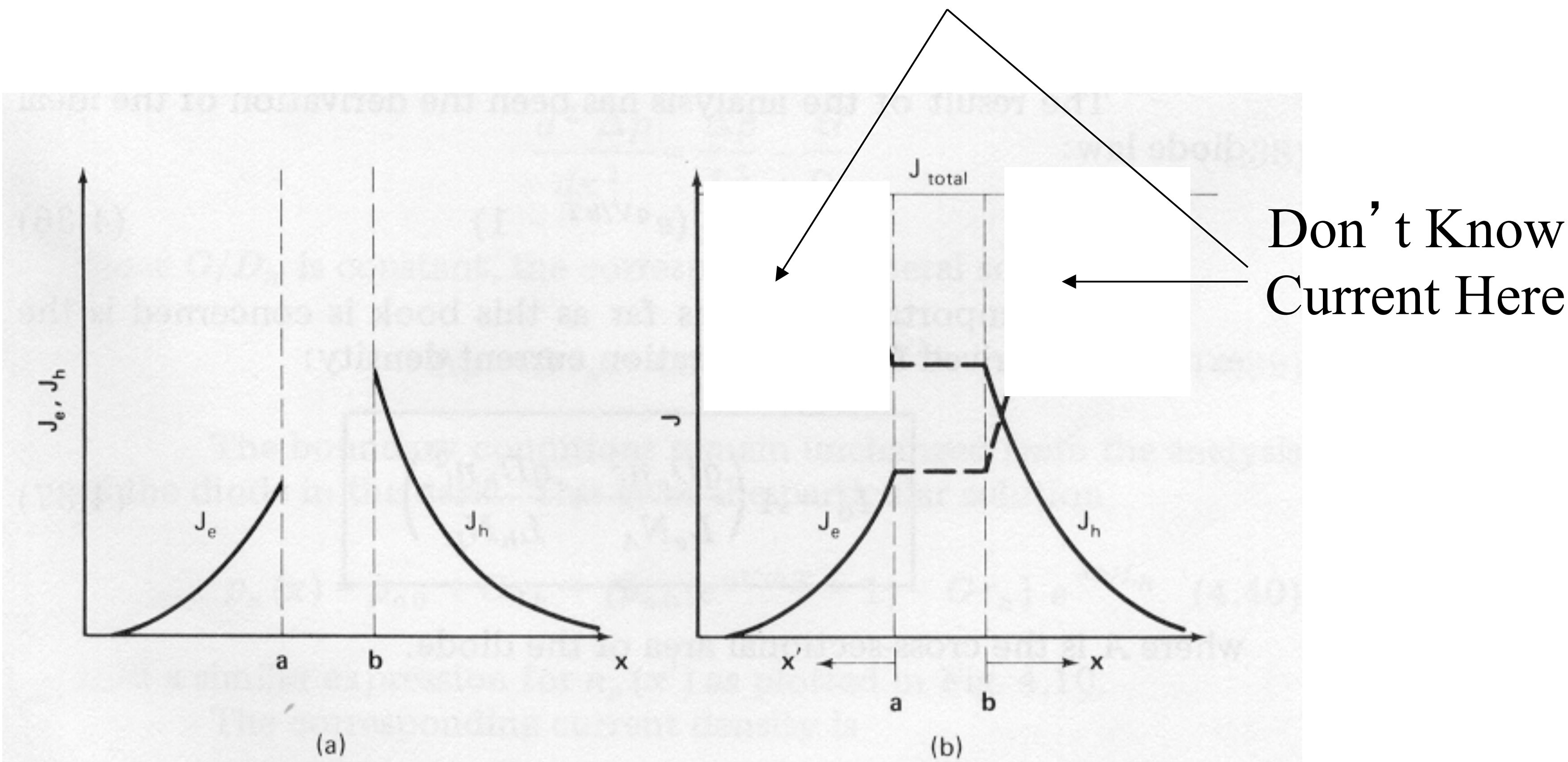


Figure 4.9. (a) Minority-carrier current densities in a *p-n* junction diode corresponding to Fig. 4.8. (b) Distribution of minority, majority, and total current densities in the diode, neglecting recombination in the depletion region.

Q: How to Find Majority Current in Quasineutral Region ?

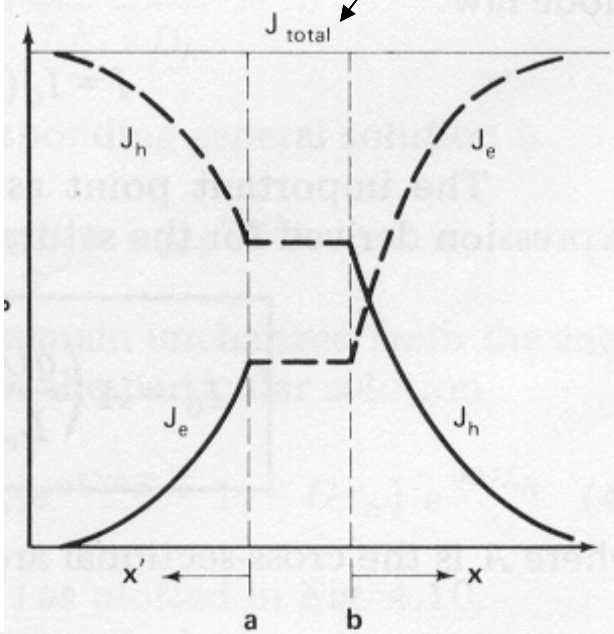
A: We Know J_{total} = Constant…

So Use Our Other Solutions

($J_{minority} \sim \exp(-x/L)$)

To Find

$$J_{total} = J_e + J_h = \left(\frac{qD_e n_{p_0}}{L_e} + \frac{qD_h p_{n_0}}{L_h} \right) \left(\exp(qV/kT) - 1 \right)$$



(a) (b)

Figure 4.9. (a) Minority-carrier current densities in a *p*-*n* junction diode corresponding to Fig. 4.8. (b) Distribution of minority, majority, and total current densities in the diode, neglecting recombination in the depletion region.

WE FOUND WHAT WE SEEK: J=J(V)

Current Density vs Voltage Across Diode:

$$J_{total} = J_e + J_h = \left(\frac{qD_e n_{p_0}}{L_e} + \frac{qD_h p_{n_0}}{L_h} \right) \left(\exp(qV/kT) - 1 \right)$$

Total Current, I (Amps), Is Just Jtotal * Area of Diode…

$$I(V) = I_0 \left(\exp(qV/kT) - 1 \right)$$

$$I_0 = A \left(\frac{qD_e n_{p_0}}{L_e} + \frac{qD_h p_{n_0}}{L_h} \right)$$

I-V Characteristics of p-n diode

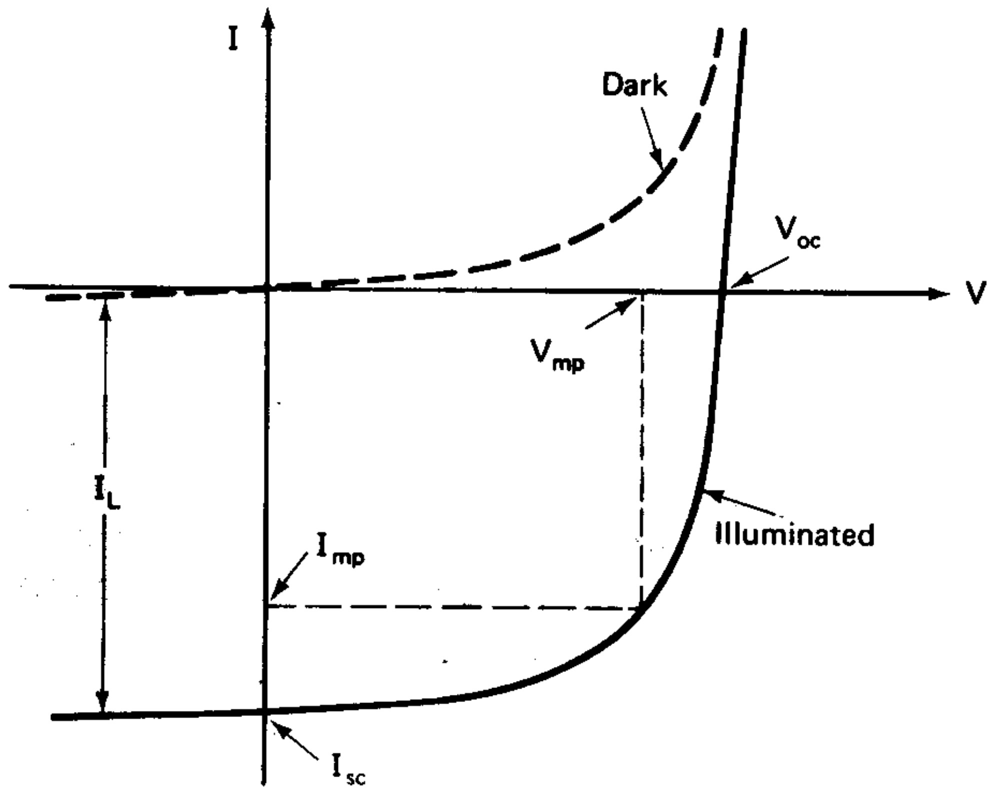


Figure 4.11. Terminal properties of a *p-n* junction diode in the dark and when illuminated.