

ELEN E3106/4106 Lecture 9

p-n Junctions Part II

Outline

- Non-equilibrium conditions (external voltage)
- Qualitative understanding of current flow
- I - V characteristics
- Carrier injection
- Reverse bias

Assignments:

Reading: Streetman and Banerjee §5.2-5.3

Homework 4 due Friday Oct. 10th by 5pm

Recap of p-n junctions so far

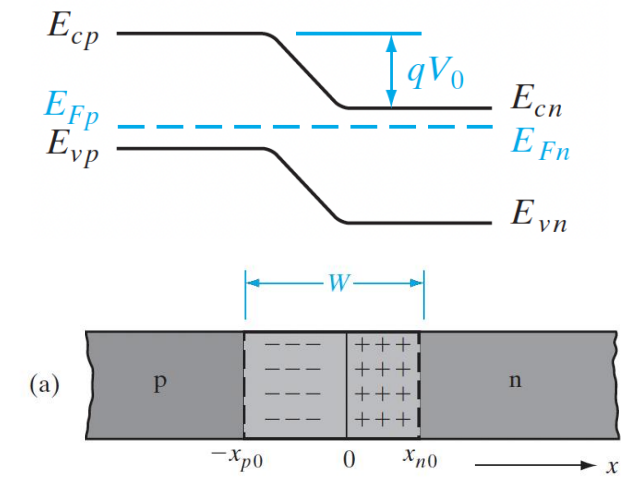
- Last lecture we discussed junctions in equilibrium
 - Called _____ (no external bias)
- We assumed the junctions were *abrupt*
 - Doping on each side is _____
- In equilibrium ($V = 0$) band diagrams,
 - _____ is constant
- Recall we found the expressions for built in voltage, _____ and depletion/transition width _____
- We have taken the depletion approximation

$$\rho(x) = -qN_a \quad (-x_p \leq x \leq 0)$$

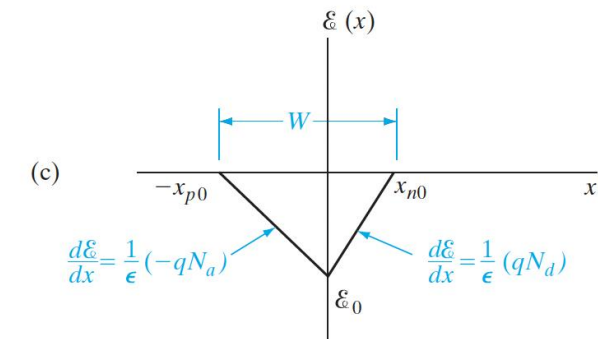
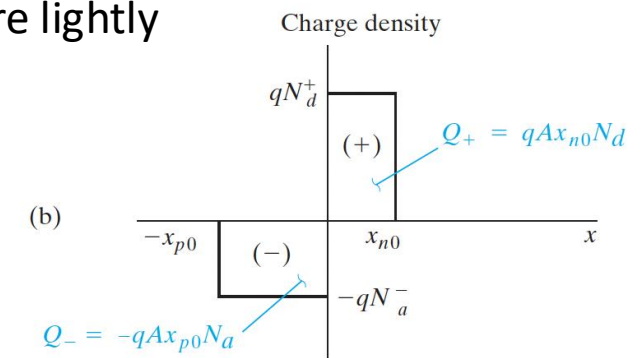
$$\rho(x) = qN_d \quad (0 \leq x \leq x_n)$$

$$\rho(x) = 0 \quad \text{elsewhere}$$

- Today, we will discuss biased ($V_{ext} \neq 0$) junctions



P-side more lightly doped



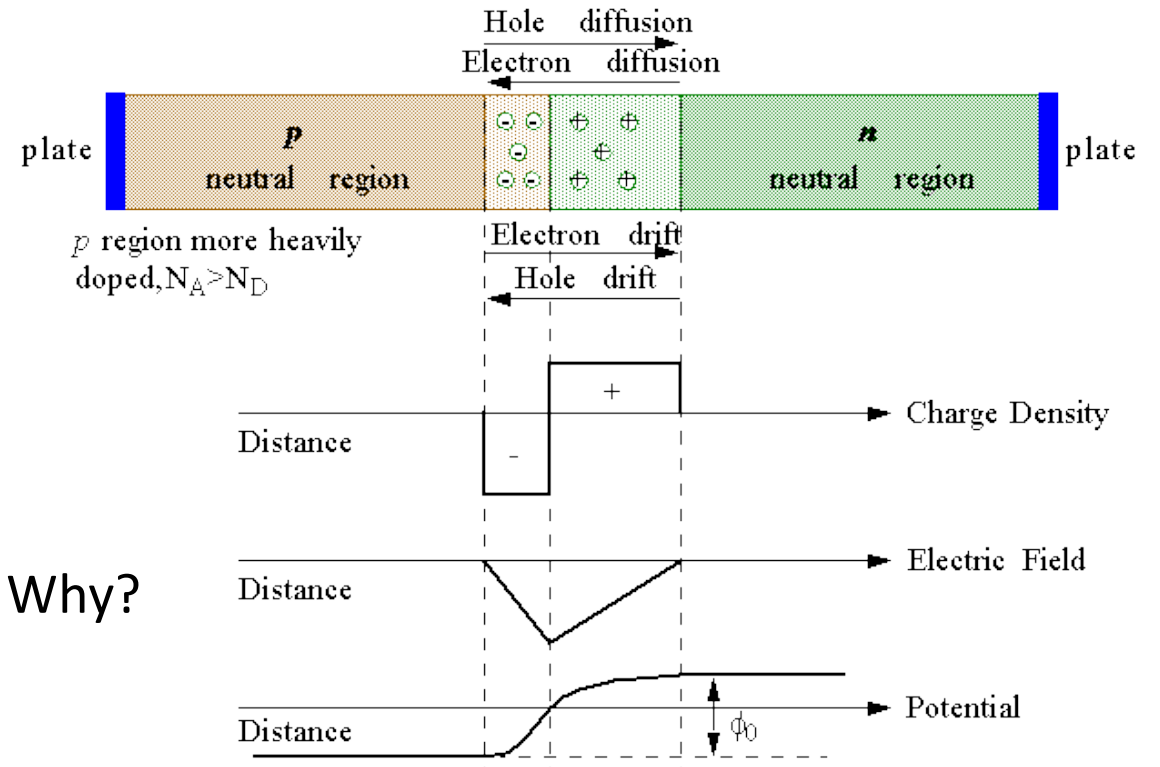
The Big Three

- Recall we discussed “the big three” for 1 dimensional problems:

• Electrostatic _____	$V(x)$	V
• Charge density _____	_____	C/cm ³
• Electric field _____	_____	V/cm

- Rules:

- The total charge in the device **must** be zero (_____).
- Potential has to be continuous.
- Potential curve is inverse to the band diagram. Why?
 - _____ is a plot of potential energy of e-
 - $E_c(x) = \text{constant} - qV(x)$
 - +V _____ band diagrams and -V _____ band diagram
- Field outside of the SCR has to be zero



- Recall: why is E-field negative?

What's the difference between a junction and a diode?

- Junction = boundary or interface between two types of materials.

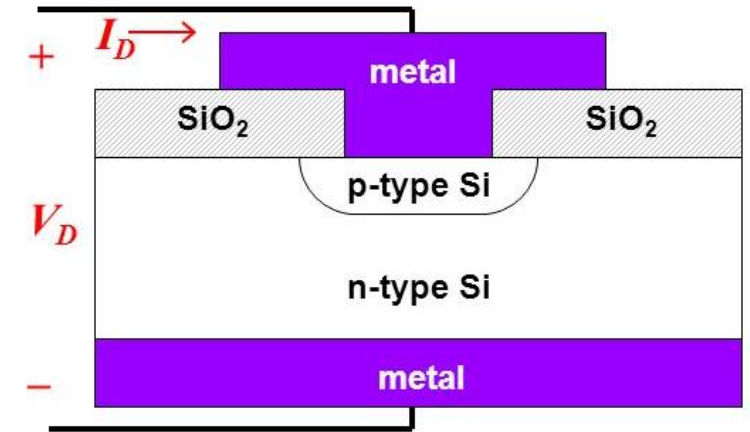
Examples:

- p-n
- ___-n
- p-p
- ____

- Diode = semiconductor device whose principle of operation is based on the p-n junction.
 - The physical structure has other practical components

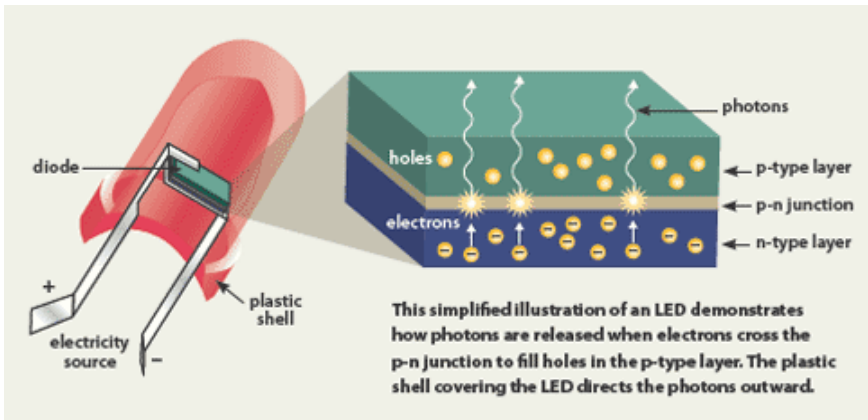
Physical structure:
(an example)

For simplicity, assume that the doping profile changes abruptly at the junction.

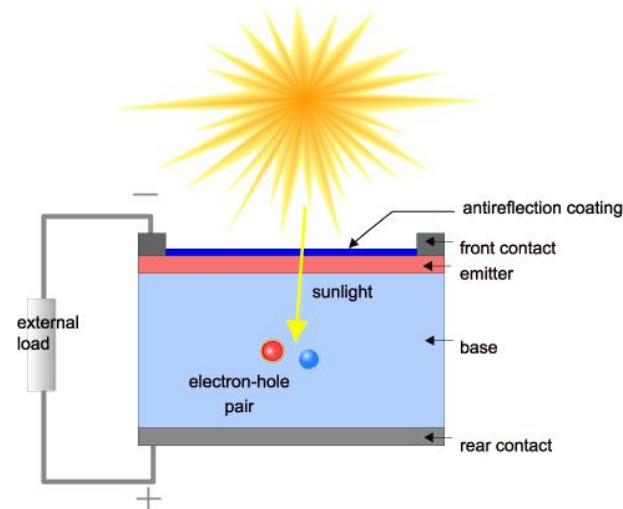


p-n Diode: Applications

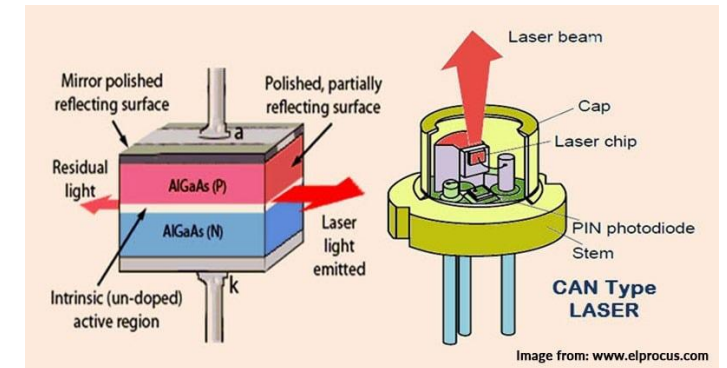
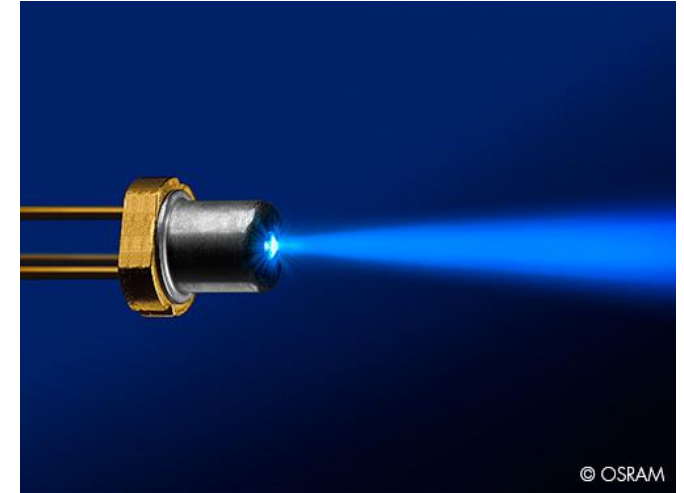
LEDs



Solar cells



Laser Diodes

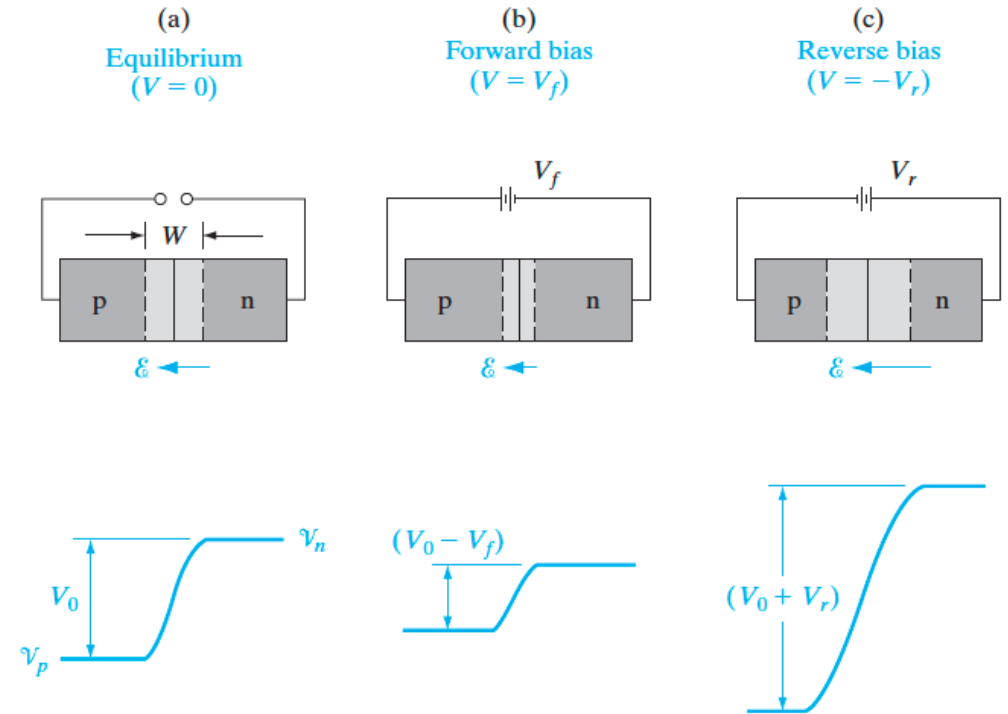


Current Flow: Qualitative description

- What happens when we leave equilibrium and apply an external bias (V)?
 - Recall: Net current flow in equilibrium is _____
- Assumption: V appears across entirely across _____ and not in the quasi-neutral regions
 - Is this actually the case?
- What does an applied bias change? A lot!
 - Electrostatic potential barrier
 - Electric field
 - Transition region width
 - Separation of energy bands
 - Diffusion currents
- Let's look at these changes **qualitatively** in further detail

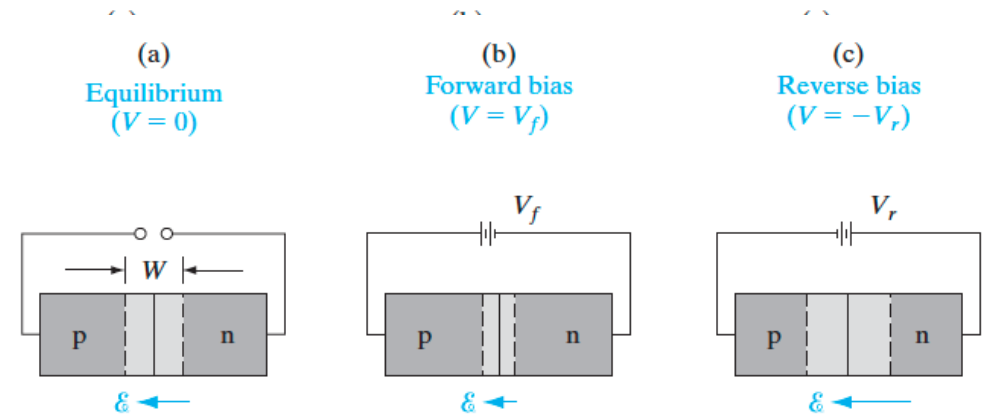
Bias effects on Electrostatic Potential Barrier

- Forward bias, ($V = V_f$) is a $+V \rightarrow$ bias is positive on the p-side relative to the n-side
- Reverse bias, ($V = -V_r$) is a $-V \rightarrow$ bias is negative on the p-side relative to the n-side
- Electrostatic potential barrier:
 - Forward bias: Lowers potential barriers (p positive with respect to n) and raises the electrostatic potential on p-side
 - Reverse bias: The opposite occurs! Electrostatic potential of the p-side is depressed relative to the n-side, and potential barrier at junction becomes larger



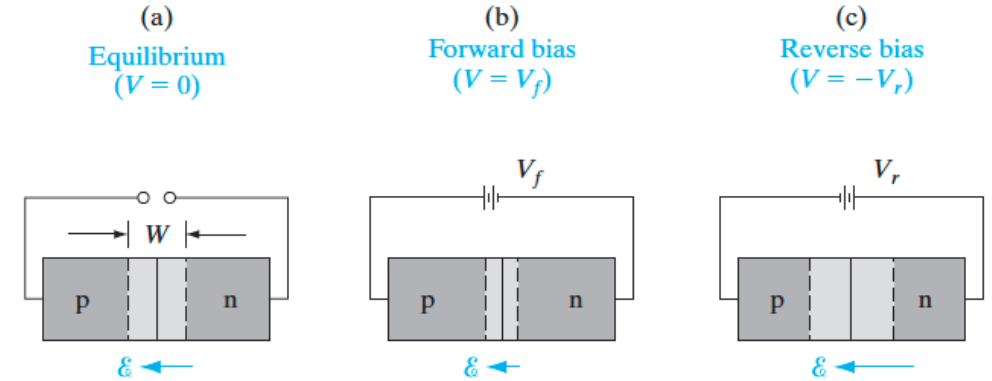
Bias effects on Electric Field

- Now we have two E-field components to consider
 - Applied arises from _____
 - Built-in arises from _____
- What are the directions of the **applied** E-fields?
- Electric field:
 - Forward bias: E-field **decreases** since applied E-field opposes the built-in field
 - Reverse bias: E-field **increases** since applied E-field is in the same direction as the built-in field



Bias effects on Transition Region Width

- Recall: W varies with the _____
- Forward bias: W **decreases** (smaller E-field, fewer uncompensated charges)
- Reverse bias: W **increases** (larger E-field, more uncompensated charges)
- We can still use the eq's on the right to calculate W , x_{p0} , x_{n0} if we replace V_0 by the new barrier height, $V_0 - V$



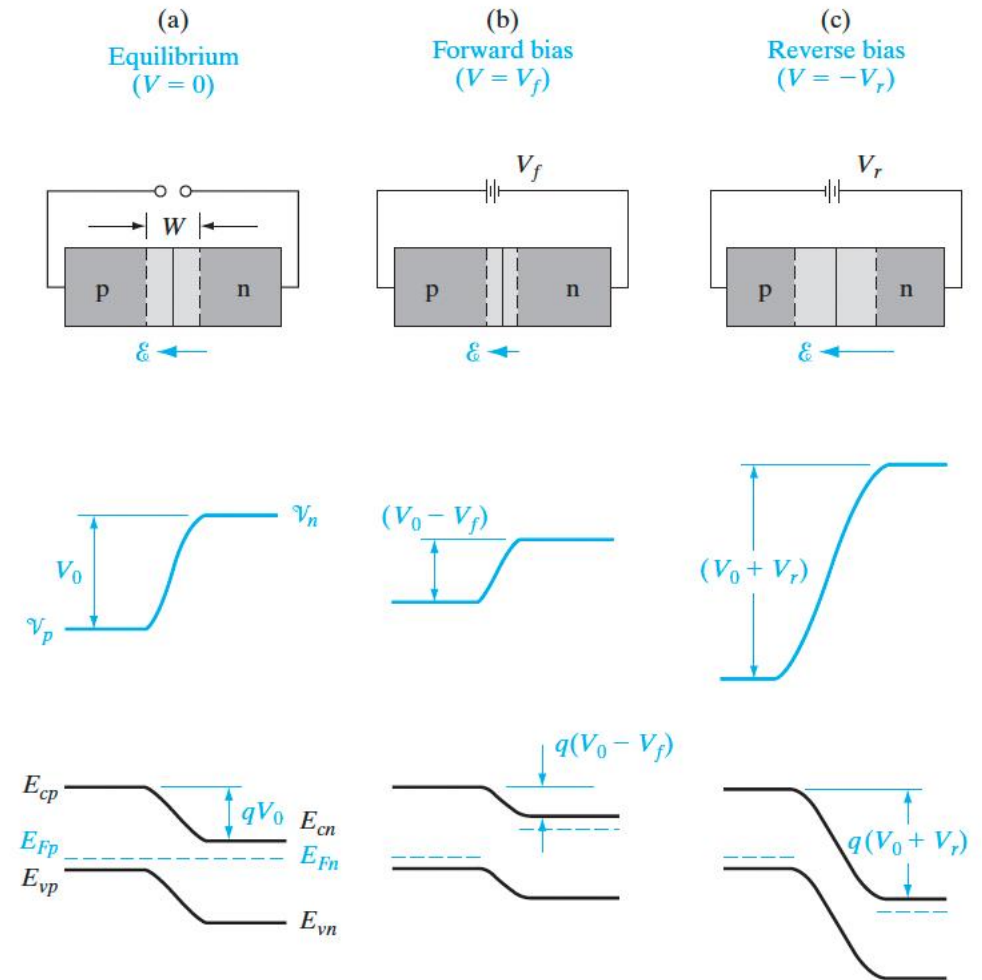
$$W = \left[\frac{2\epsilon V_0}{q} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2} = \left[\frac{2\epsilon V_0}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right) \right]^{1/2}$$

$$x_{p0} = \frac{W N_d}{N_a + N_d} = \frac{W}{1 + N_a/N_d} = \left\{ \frac{2\epsilon V_0}{q} \left[\frac{N_d}{N_a(N_a + N_d)} \right] \right\}^{1/2}$$

$$x_{n0} = \frac{W N_a}{N_a + N_d} = \frac{W}{1 + N_d/N_a} = \left\{ \frac{2\epsilon V_0}{q} \left[\frac{N_a}{N_d(N_a + N_d)} \right] \right\}^{1/2}$$

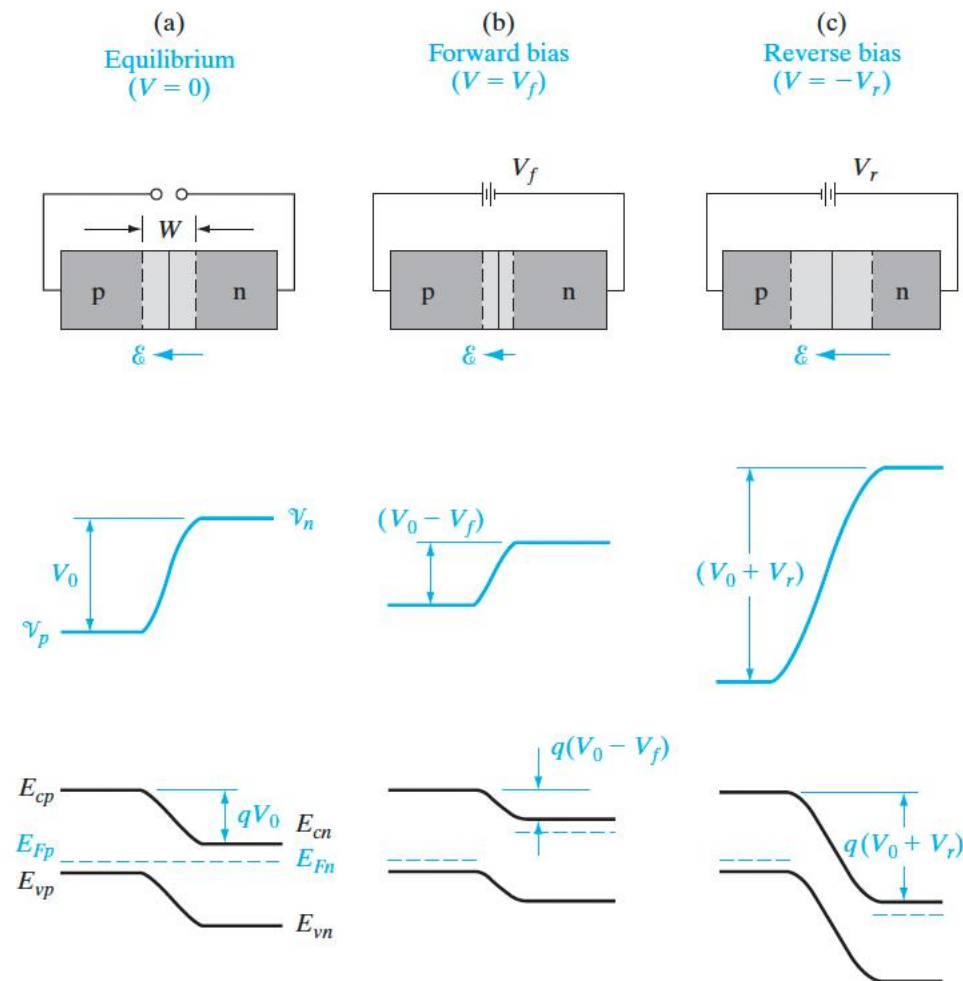
Bias effects on Separation of Energy Bands, Fermi Level

- This is a direct function of the electrostatic potential barrier at the junction
- Is the Fermi level still constant?
 - Shifting of the energy bands under bias implies a separation of the Fermi levels on either side of the junction
 - The Fermi levels _____ and _____ in the two QNRs are separated by an energy equal to qV_{total}
- Forward bias: Separation **decreases** by compared to equilibrium and is $q(V_0 - V_f)$
- Reverse bias: Separation **increases** by compared to equilibrium and is $q(V_0 + V_r)$



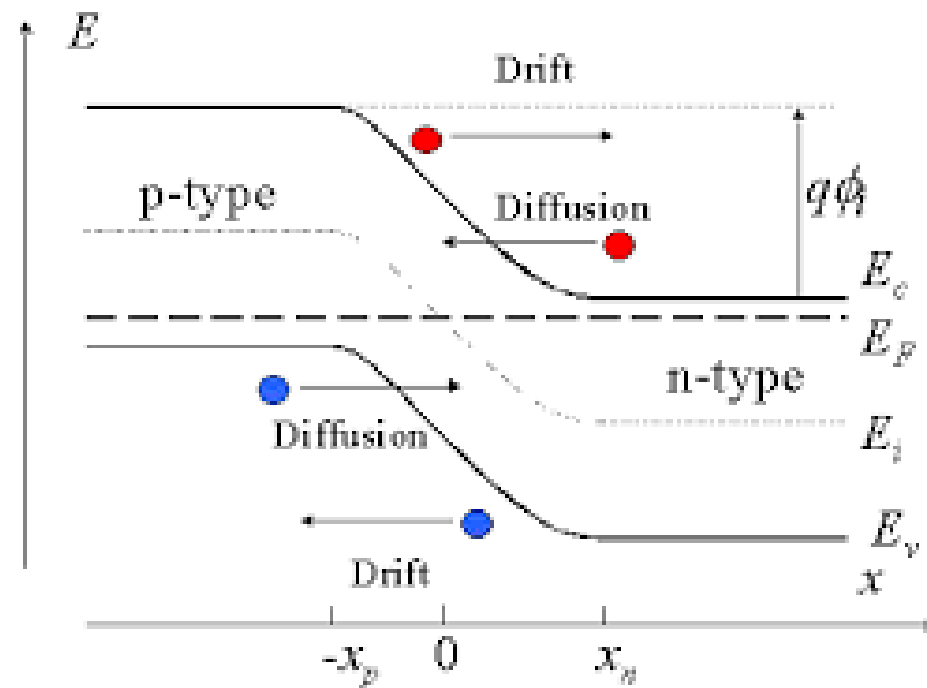
Bias effects on Diffusion Current

- Recall:
 - Diffusion of majority h^+ on p-side to n-side
 - Diffusion of majority e^- on n-side to p-side
- Both carriers have to surmount the potential energy barrier
- Equilibrium: some e^- and h^+ have enough energy to diffuse across barrier
- Forward bias: Barrier is lower, so more e^- and h^+ can diffuse \rightarrow diffusion currents increase
- Reverse bias: Barrier is higher, so virtually no e^- and h^+ can diffuse \rightarrow diffusion currents are usually negligible



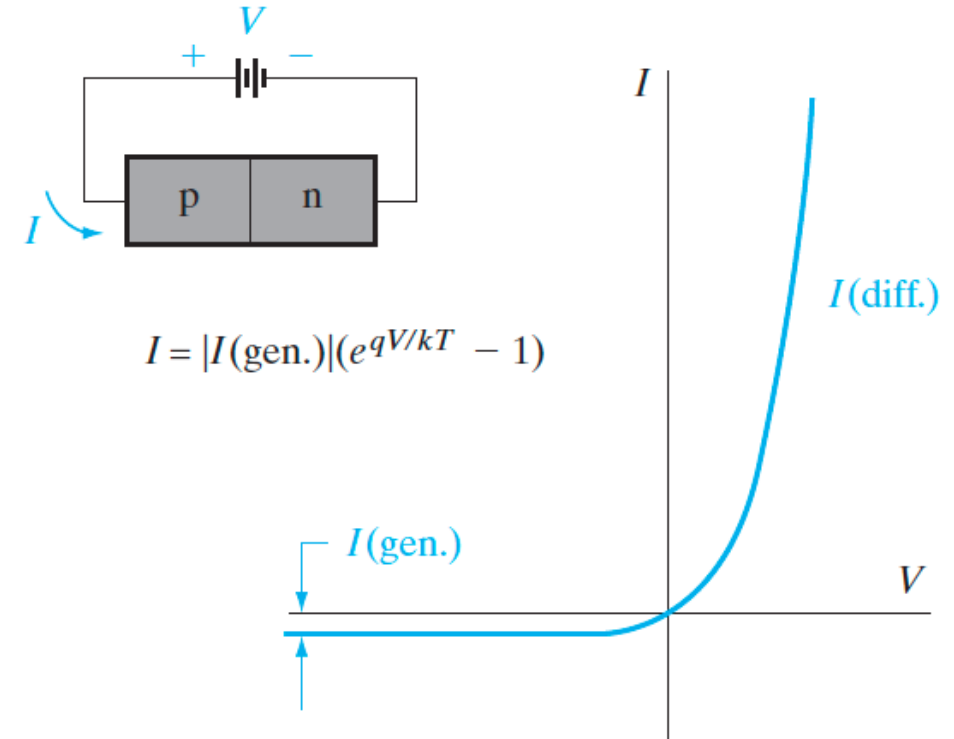
Bias effects on Drift Current

- Relative insensitive to the height of the potential barrier
- The electron and hole drift currents at the junction are **independent** of applied voltage
- Why?
- Drift current is limited by how often carriers are swept down the barrier
- Imagine: Every minority e- on the p-side which wanders into the transition region will be swept down the potential energy hill, whether the hill is small or large



Generation Current

- Minority carriers on each side of the junction are required to participate in drift
- What generates EHPs? _____ or _____
- Current due to drift of the thermally generated EHPs across the junction is called the *generation current*
- Magnitude relies entirely on rate of generation of EHPs
 - Important for optoelectronics based on p-n diodes!

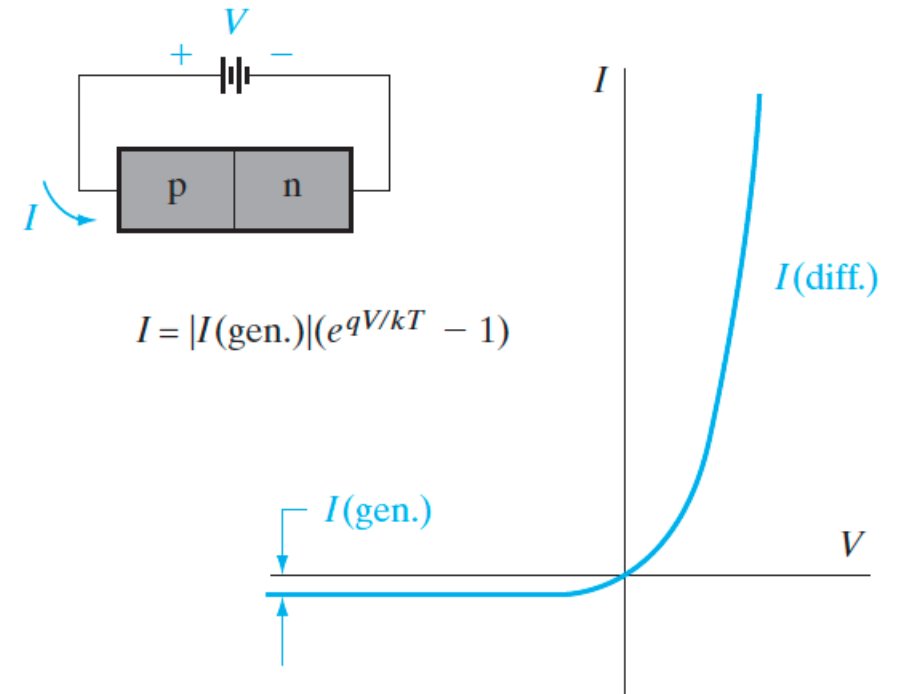


Total Currents Across the Junction

- Total current flow is the sum of diffusion and drift components

From left to right on diagram:

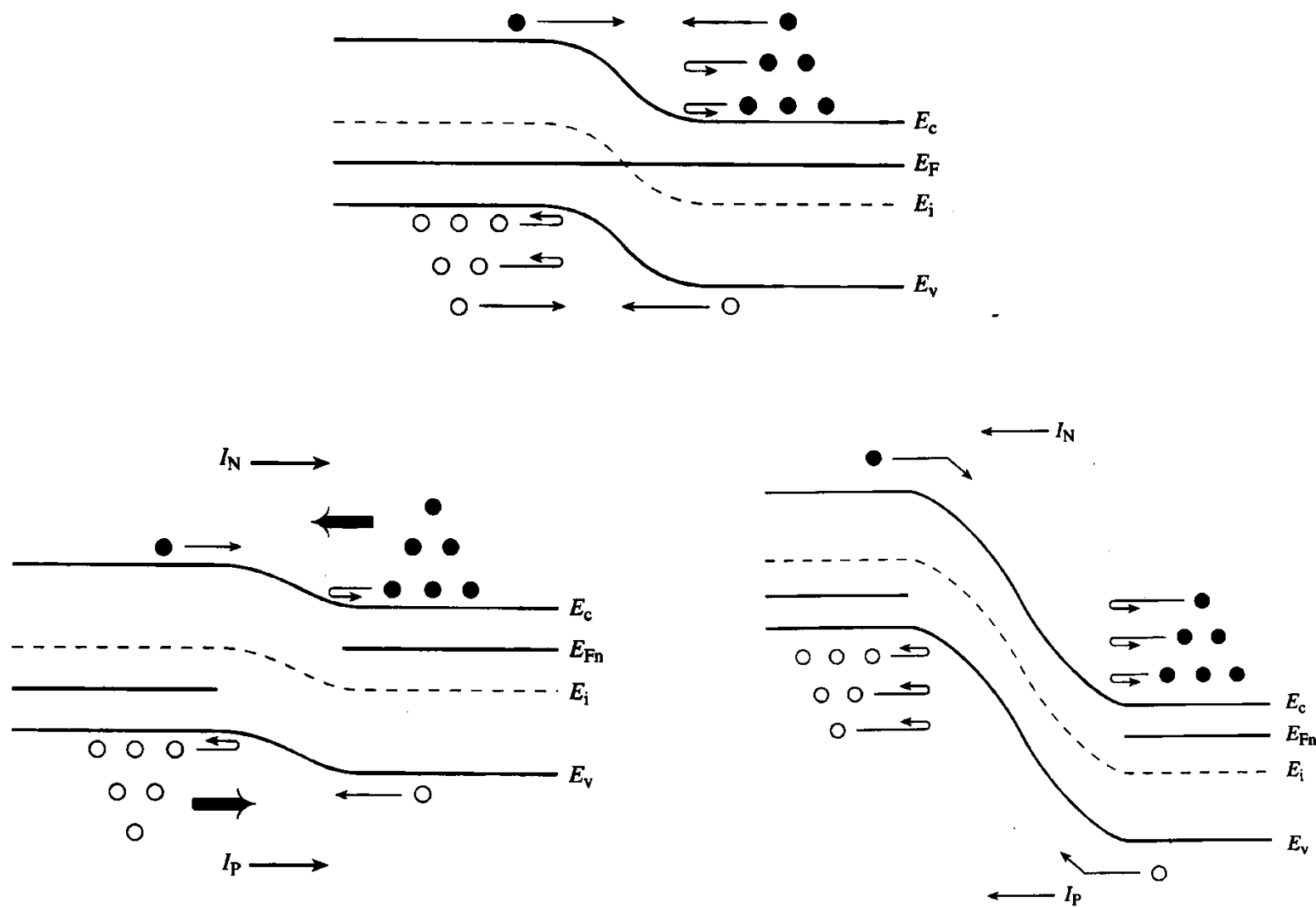
- Reverse bias: barrier to diffusion is large so diffusion currents are negligible. Only current is a relatively small, generation current _____ which is due to minority carrier drift
- Equilibrium ($V=0$): Net current flow is 0
 - Drift and diffusion cancel each other out
- Forward bias: Diffusion current increases exponentially as increased (+)V further lowers the barrier. Drift current is the same and comparatively small
- **Major point: Current flows relatively freely in forward bias, but almost no current flows in reverse bias!**



$$I = I(\text{diff.}) - |I(\text{gen.})| = 0 \text{ for } V = 0$$

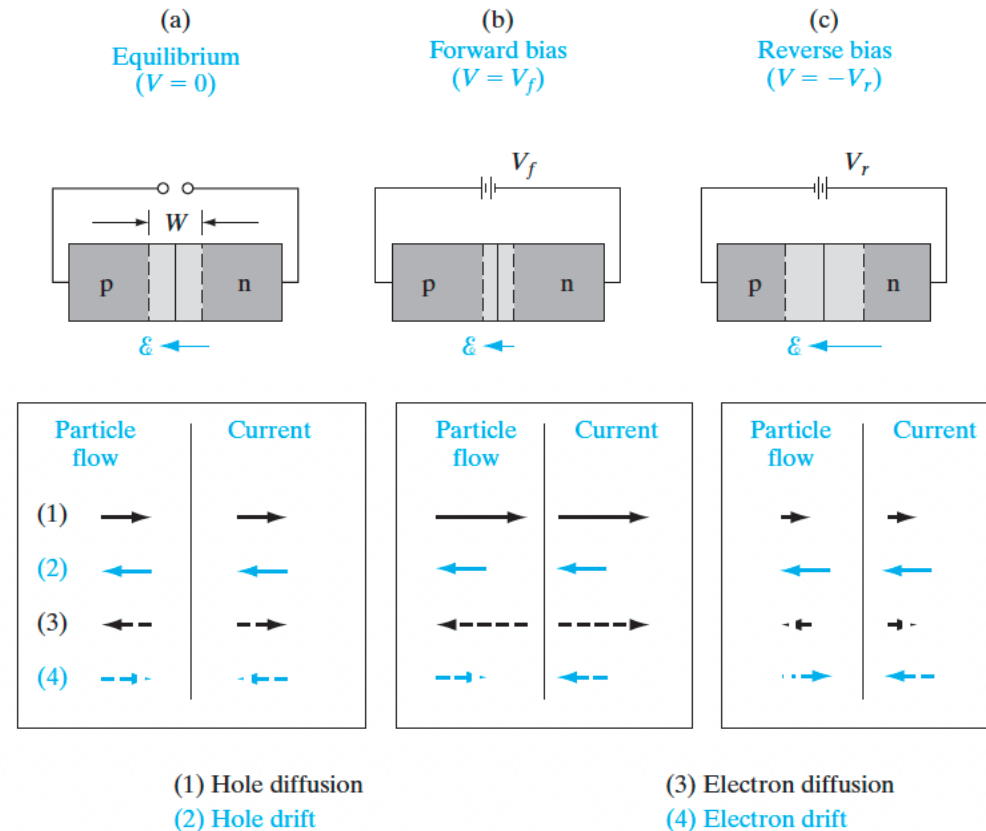
$$I = I_0(e^{qV/kT} - 1)$$

Visualizing Directions of Particle and Current Flow



Visualizing Directions of Particle and Current Flow

- Directions of the four components of particle flow within the transition region, and the resulting current directions.
- Recall: electron current is opposite to the direction of flow of electrons

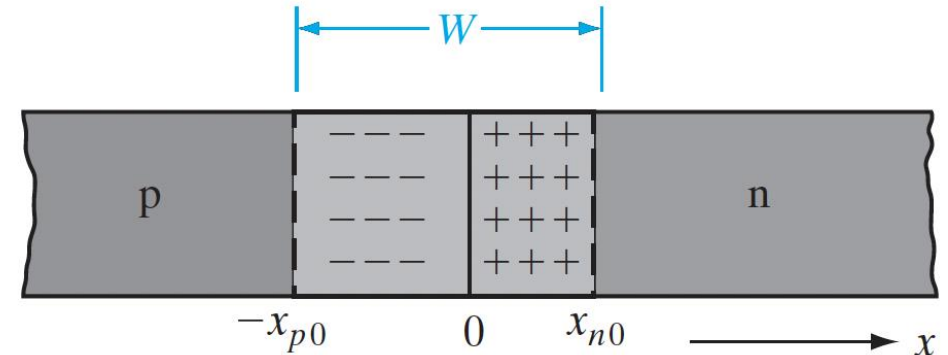


Minority Carrier Injection in Forward Bias

- Recall: For low-level injection, we can neglect changes in majority carrier concentration
- As we apply forward bias, we increase the minority carrier concentration:

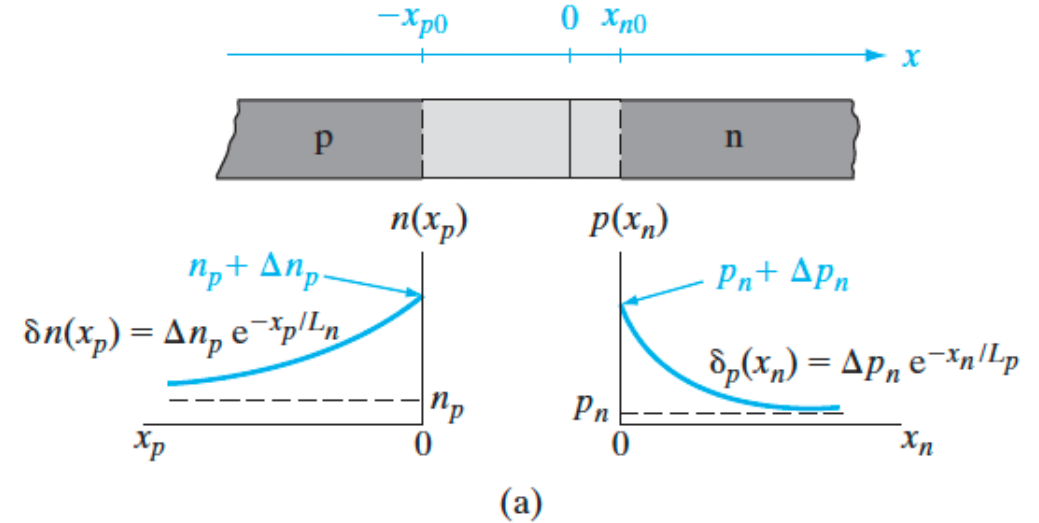
$$\frac{p(x_{n0})}{P_n} = e^{qV/kT}$$

- Conversely, $p(x_{n0})$ is _____ below equilibrium value _____ in reverse bias



Excess Minority Carrier Spatial Distributions

- What happens to these injected carriers?
 - They _____
 - Recall: on average carriers diffuse a distance _____ before recombining with _____
- The excess carrier solution is _____
- Note: x_n and x_p are the distances measured from the edge of the _____
- We are assuming not recombination in the _____



Distribution of excess minority carriers that have been steady-state injected in FB

$$\delta n(x_p) = \Delta n_p e^{-x_p/L_n} = n_p (e^{qV/kT} - 1) e^{-x_p/L_n}$$

$$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n (e^{qV/kT} - 1) e^{-x_n/L_p}$$

The Ideal Diode Equation

- Hole diffusion current at any point in the n material can be found:

$$I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n} = qA \frac{D_p}{L_p} \Delta p_n e^{-x_n/L_p} = qA \frac{D_p}{L_p} \delta p(x_n)$$

- Total _____ current injected in the n material at the junction:

$$I_p(x_n = 0) = \frac{qAD_p}{L_p} \Delta p_n = \frac{qAD_p}{L_p} p_n (e^{qV/kT} - 1)$$

- Total _____ current injected into the p material at the junction:

$$I_n(x_p = 0) = -\frac{qAD_n}{L_n} \Delta n_p = -\frac{qAD_n}{L_n} n_p (e^{qV/kT} - 1)$$

- The total diode current is simply the sum: (true for RB and FB)

$$I = I_p(x_n = 0) - I_n(x_p = 0) = \frac{qAD_p}{L_p} \Delta p_n + \frac{qAD_n}{L_n} \Delta n_p$$

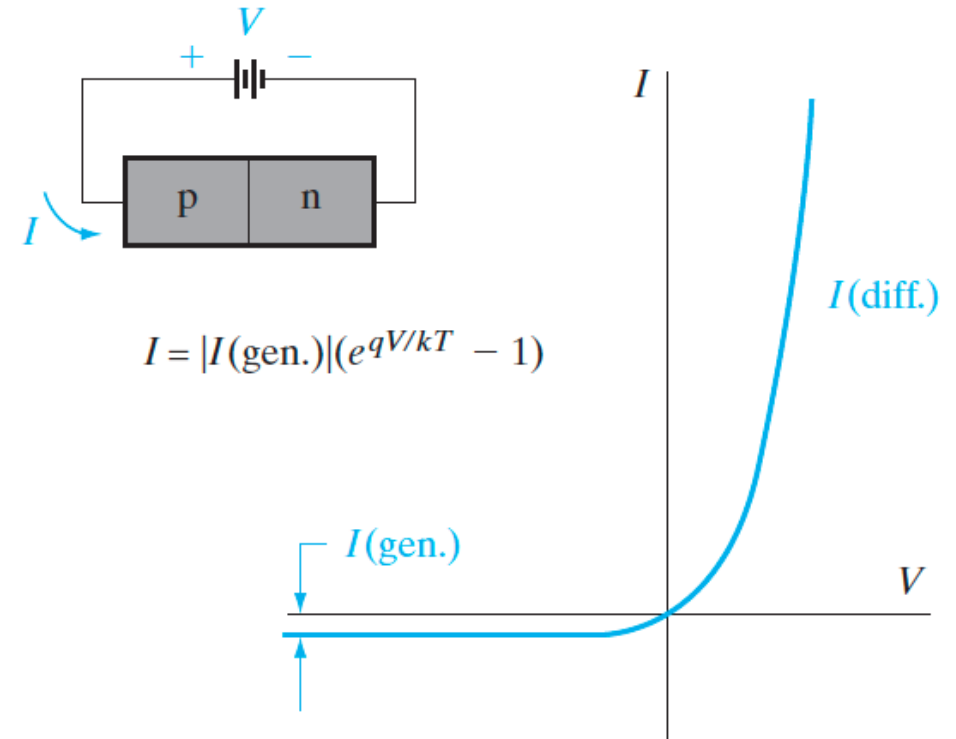
$$I = qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) (e^{qV/kT} - 1) = I_0 (e^{qV/kT} - 1)$$

Reverse Saturation Current

- Denoted _____
 - Units: A

$$I = -qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right) = -I_0$$

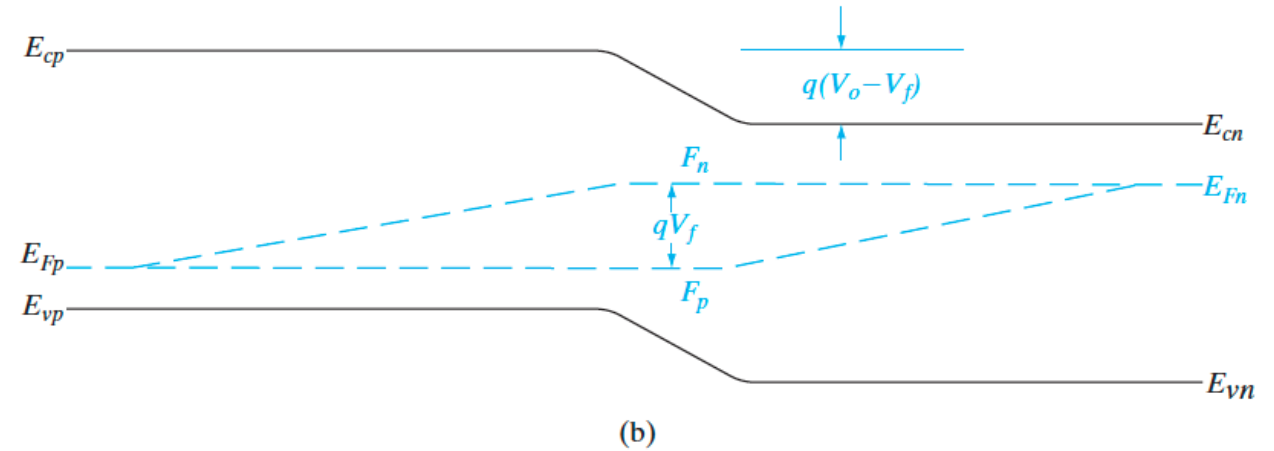
- Holds as long as V_r is larger than a few kT/q
- Equal to the absolute value of _____



Energy Band Diagram: Forward Bias

- E_F splits into quasi-Fermi levels
- Within W , they are separated by

$$pn = n_i^2 e^{(F_n - F_p)/kT} = n_i^2 e^{(qV)/kT}$$

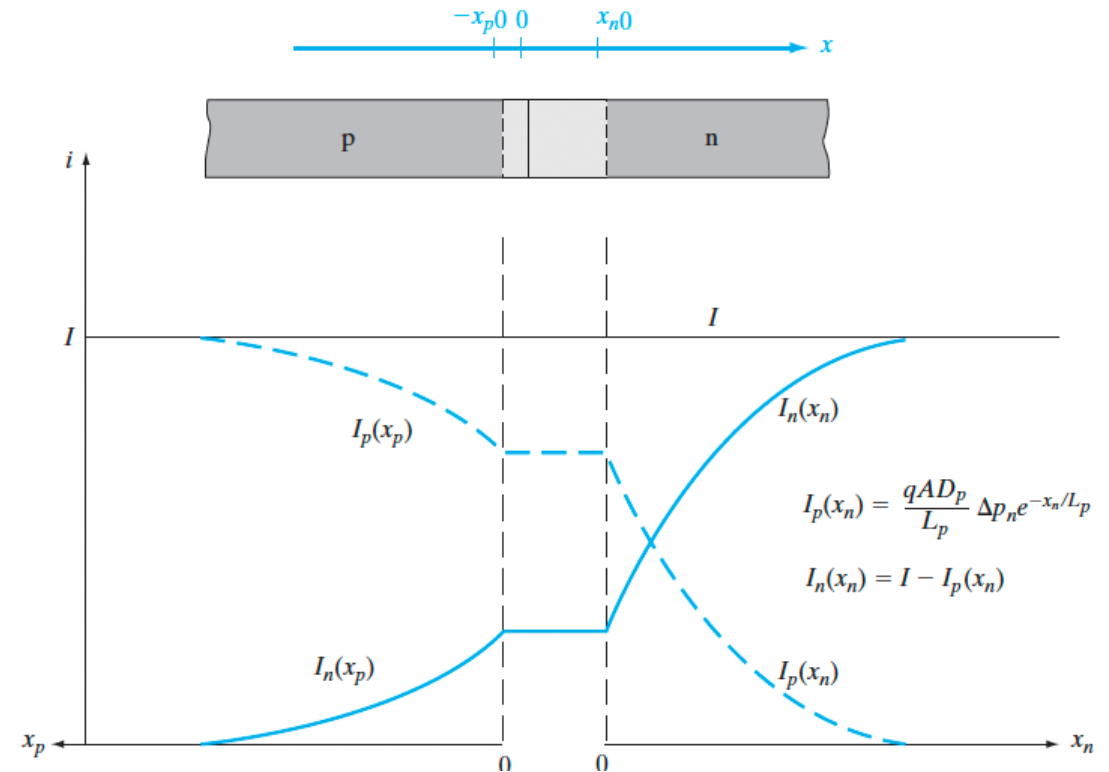


- On either side of junction, minority carrier quasi-Fermi level varies the most
- Majority carrier quasi-Fermi level close to original E_F
- In QNRs, minority carrier quasi-Fermi levels vary linearly until they merge with the Fermi levels

Electron and Hole Components of Currents in Forward Biased p-n Junction

- Which side has higher doping?
- Implication of diode equation: the total current at the junction is dominated by injection of carriers from the more heavily doped side into the side with lesser doping.

$$I = qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) (e^{qV/kT} - 1) = I_0 (e^{qV/kT} - 1)$$

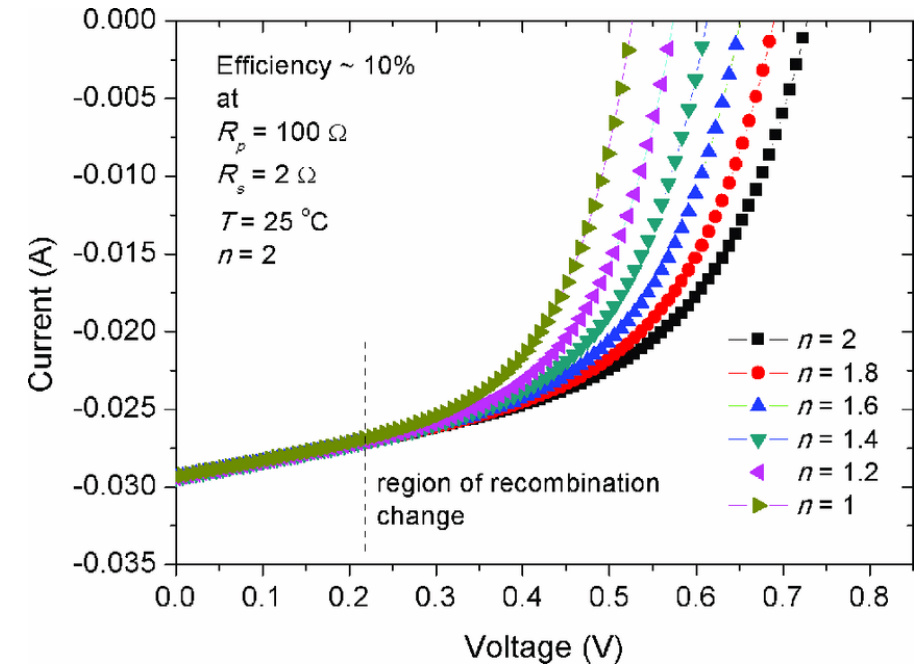


Ideality Factor

- So far, we have assumed recombination and generation do not take place in the depletion region
- But in reality, recombination in W can be significant
- Current due to recombination within W is proportion to n_i and increases exponentially with forward bias
- We can capture this effect by modifying the ideal diode equation:

$$I = I'_0(e^{qV/nkT} - 1)$$

- Where ____ is the ideality factor and varies between 1 and 2
- What does n depend on? _____ and _____



Reverse Bias and Minority Carrier Extraction

- From our earlier discussion,
 - E-field across W _____
 - Current is due only to minority carrier _____ across the junction
 - Current is supplied by EHP generation in the _____

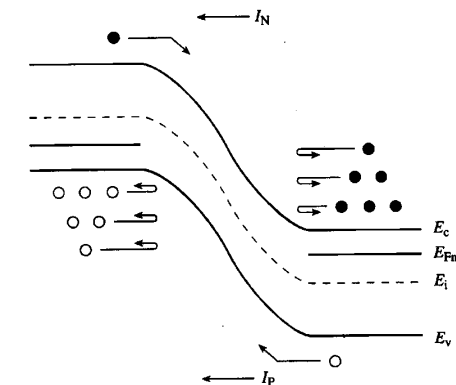
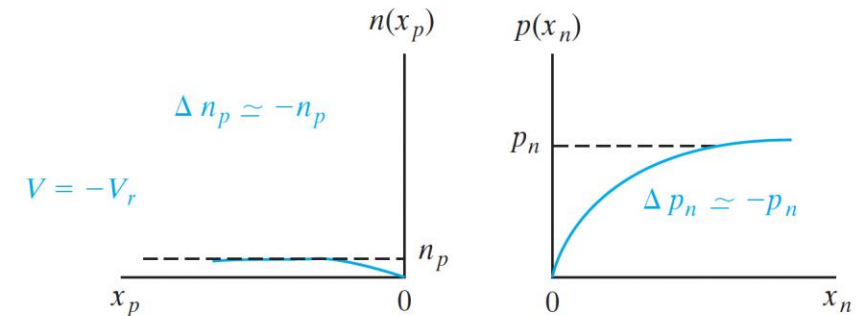
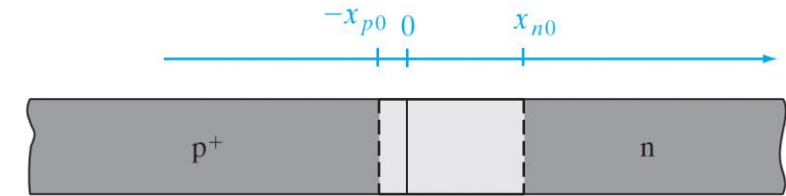
- Recall, reverse saturation current:

$$I = -qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) = -I_0$$

- The same excess carrier distributions from earlier can be used, with $V = -V_r$, and we find:
- Minority carrier concentration at each edge of W becomes _____
- Extraction occurs because minority carriers at edges of W are swept down the barrier at the junction to the other side, but they are not replaced by an opposing diffusion of carriers

$$\Delta p_n = p_n (e^{q(-V_r)/kT} - 1) \approx -p_n \quad \text{for } V_r \gg kT/q$$

$$\Delta n_p \approx -n_p.$$



Junction (Depletion) Capacitance

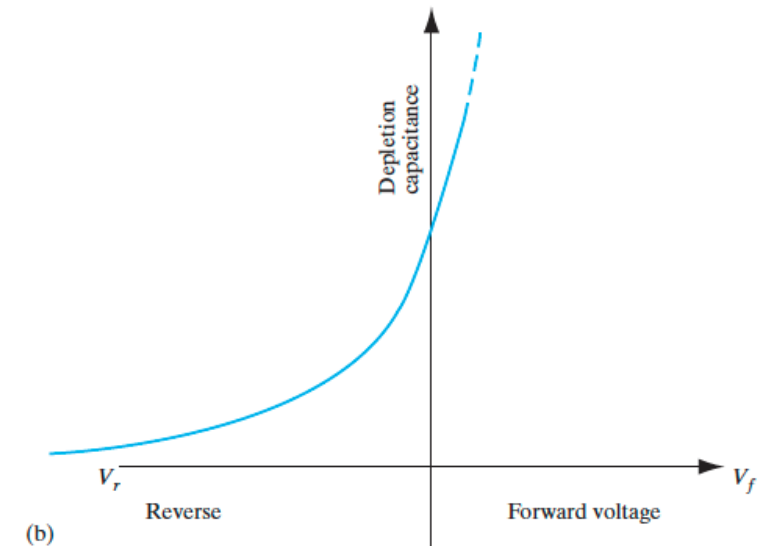
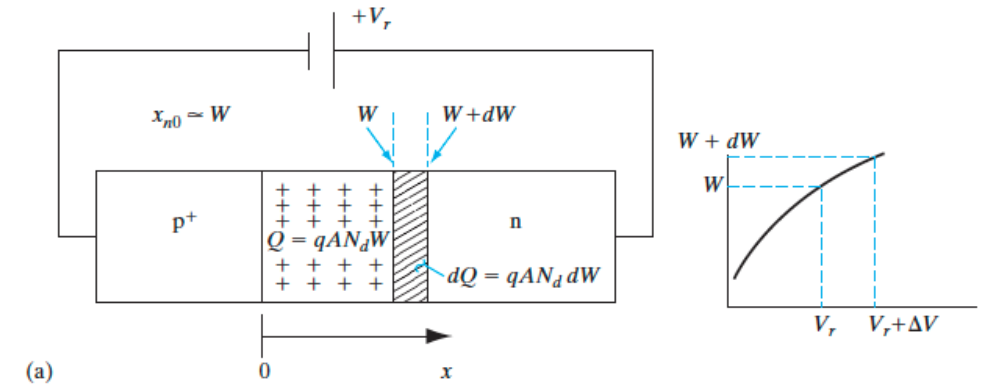
- In reverse bias ($V < 0$) fixed charge is *stored* in the junction, as the depletion width widens with more negative V .
- Why? How does W change with voltage?

$$C = \left| \frac{dQ}{dV} \right|$$

$$C_j = \left| \frac{dQ}{d(V_0 - V)} \right| = \frac{A}{2} \left[\frac{2q\epsilon N_d N_a}{(V_0 - V) N_d + N_a} \right]^{1/2}$$

- _____ is a _____-variable capacitance, unlike parallel plate
- Sort of like a parallel plate cap but more complicated
 - W corresponds to _____

$$C_j = \epsilon A \left[\frac{q}{2\epsilon(V_0 - V)} \frac{N_d N_a}{N_d + N_a} \right]^{1/2} = \frac{\epsilon A}{W}$$



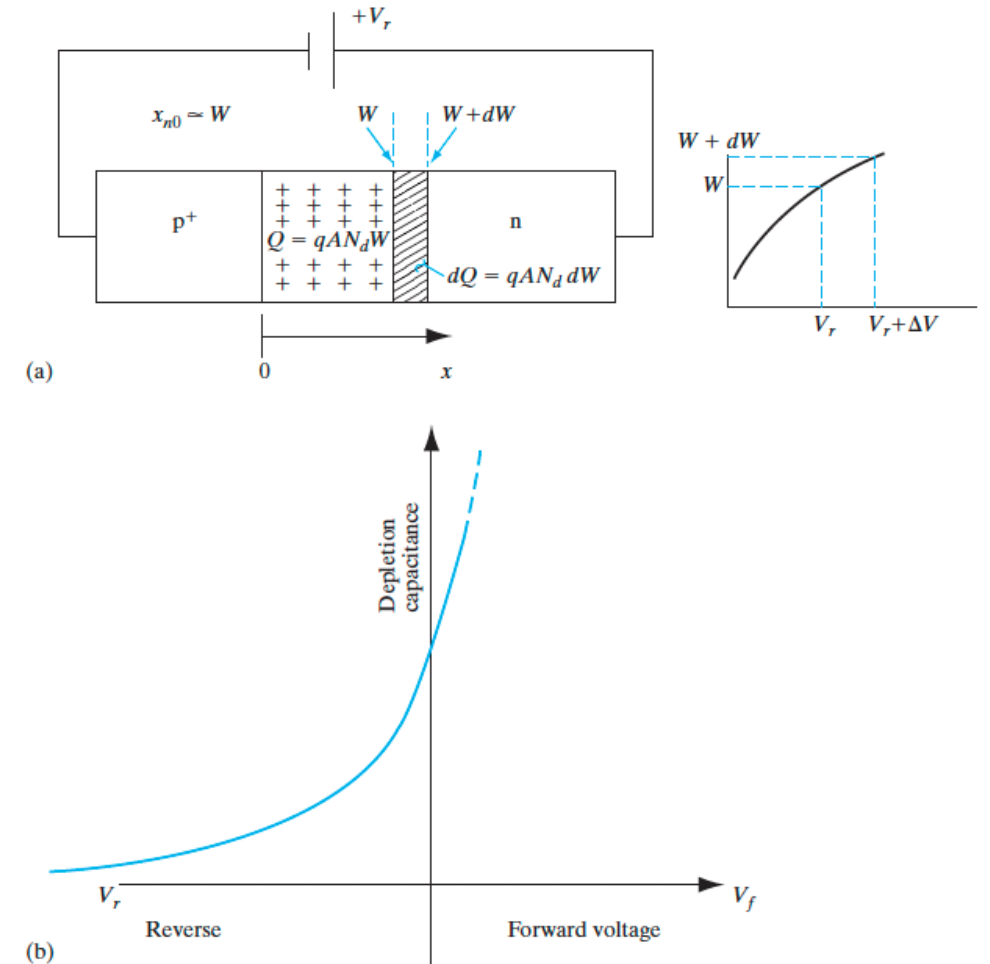
Junction Capacitance in Asymmetric Junctions

- What about in an asymmetrically doped diode?

For p^+-n ,

- W extends primarily into _____
- _____ is negligible
- $N_+ \gg N_-$
- Capacitance is determined by only ONE of the doping concentrations

$$C_j = \frac{A}{2} \left[\frac{2q\epsilon}{V_0 - V} N_d \right]^{1/2} \text{ for } p^+-n$$



Measuring Junction Capacitance

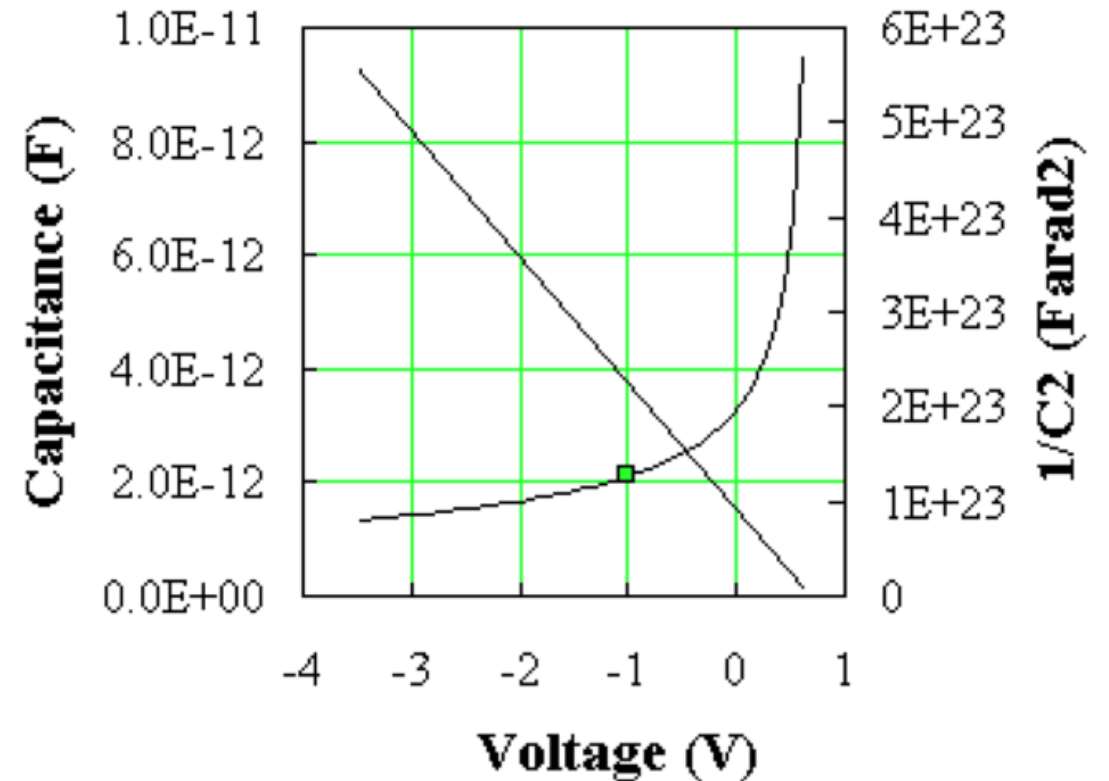
- So, if we measure and plot $\frac{1}{C_j^2}$ vs V , we can get the _____

- On the _____ side of an asymmetric junction

$$\frac{1}{C_J^2} = \left(\frac{W}{\epsilon_s A} \right)^2 \cong \frac{2}{A^2 q \epsilon_s N} (V_0 - V)$$

- Slope =

- We can also find the _____
 - $= \frac{kT}{q} \ln \left(\frac{N_a N_d}{n_i^2} \right)$

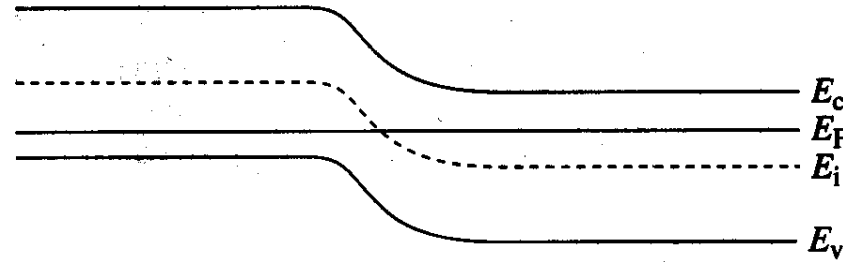


Summary of main points

- Forward bias:
 - Current flows freely. Magnitude increases exponentially as bias is increased.
 - Forward current is dominated by **diffusion** of minority carriers
 - Width of depletion region is decreased
 - Excess of carriers compared to equilibrium (injection)
- Reverse bias:
 - Almost no current flows
 - More reverse bias means a broader depletion region
 - Reverse saturation current (___ = _____) dominated by **drift** of minority carriers
 - Width of depletion region is increased
 - Fewer carriers than in equilibrium (extraction)
- General trends:
 - More doping = narrower junction
 - Depletion region extends further into more lightly doped side

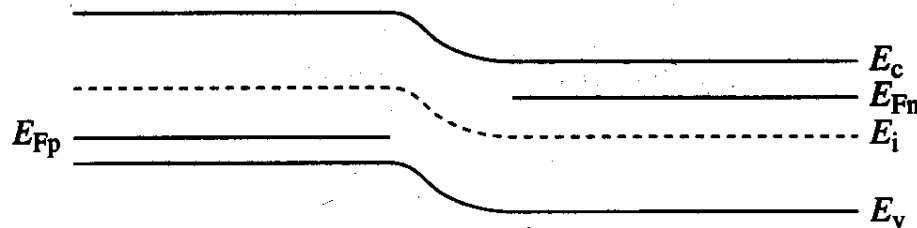
Visual Summary

Equilibrium
($V = 0$)



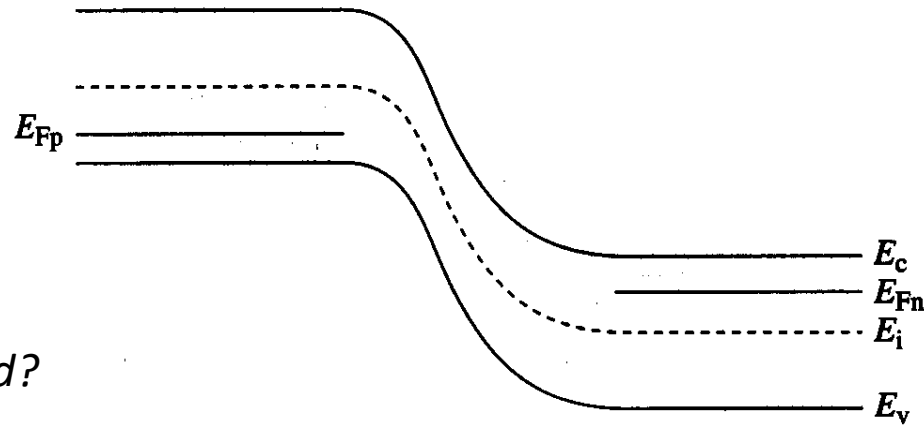
(a) Equilibrium ($V_A = 0$)

Forward bias
($V > 0$)



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

Reverse bias
($V < 0$)



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

Which side more lightly doped?

