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

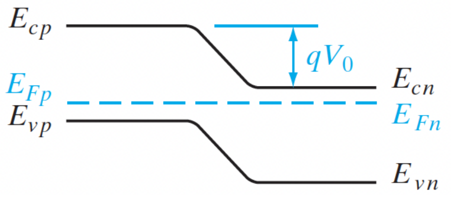
Assignments:
Reading: Streetman and Banerjee §5.2-5.3
Homework 4 due Friday Oct. 10th by 5pm

Recap of p-n junctions so far

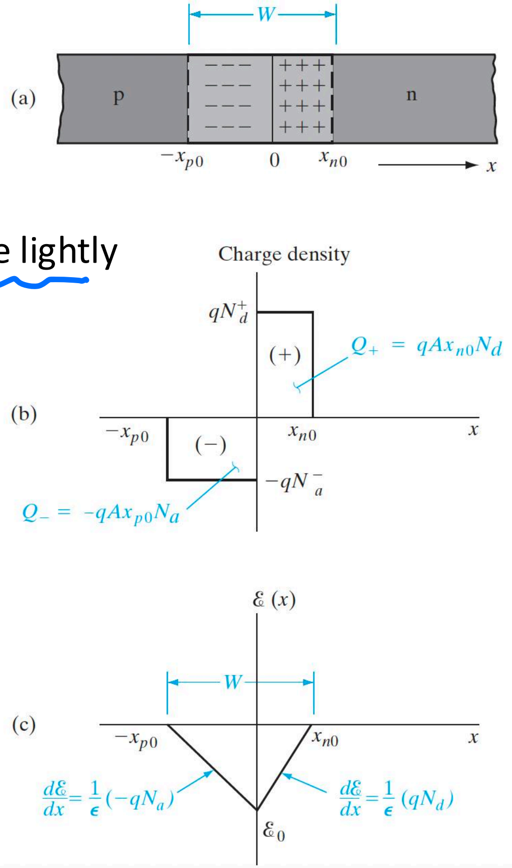
- Last lecture we discussed junctions in equilibrium
  - Called unbiased (no external bias)
- We assumed the junctions were *abrupt*
  - Doping on each side is uniform
- In equilibrium (V = 0) band diagrams,
  - E_F is constant
- Recall we found the expressions for built in voltage, V_0 and depletion/transition width W
- We have taken the depletion approximation

$$\rho(x) = -qN_a \quad (-x_p \leq x \leq 0)$$
$$\rho(x) = qN_d \quad (0 \leq x \leq x_n)$$
$$\rho(x) = 0 \quad \text{elsewhere in QNRs}$$

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



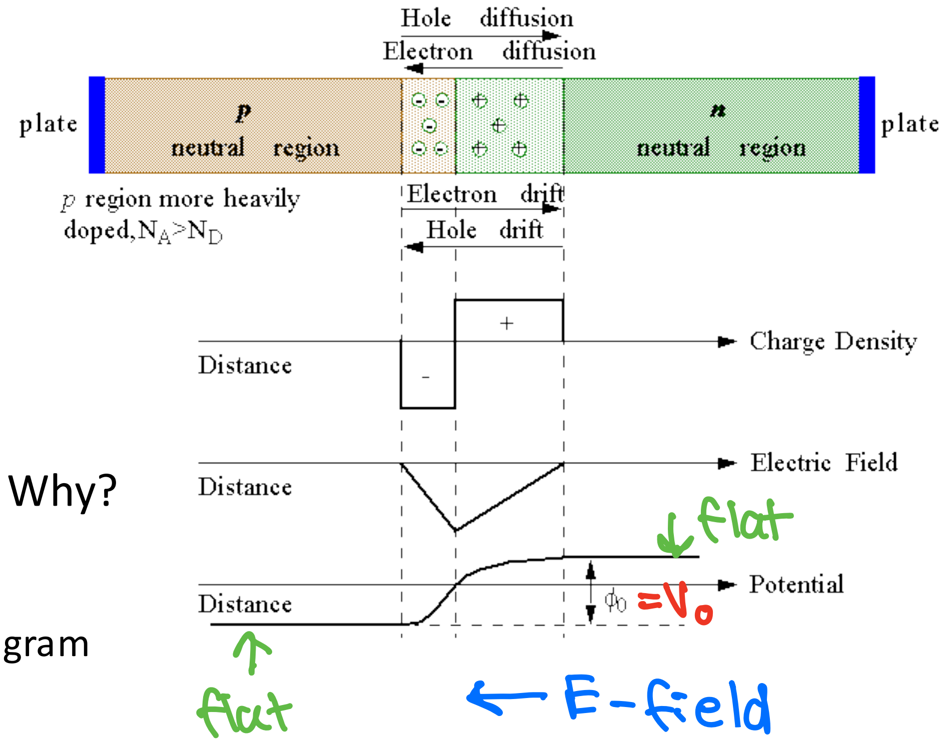
P-side more lightly doped



Sources: Textbook

The Big Three

- Recall we discussed "the big three" for 1 dimensional problems:
  - Electrostatic potential $V(x)$ V
  - Charge density $\rho(x)$ C/cm^3
  - Electric field $E(x)$ V/cm



- Rules:
  - The total charge in the device **must** be zero (charge neutrality).
  - Potential has to be continuous.
  - Potential curve is inverse to the band diagram. Why?
    - Band diagram is a plot of potential energy of e-
    - $E_c(x) = constant - qV(x)$
    - +V lower band diagrams and –V raises band diagram
  - Field outside of the SCR has to be zero

- Recall: why is E-field negative?

  -x direction

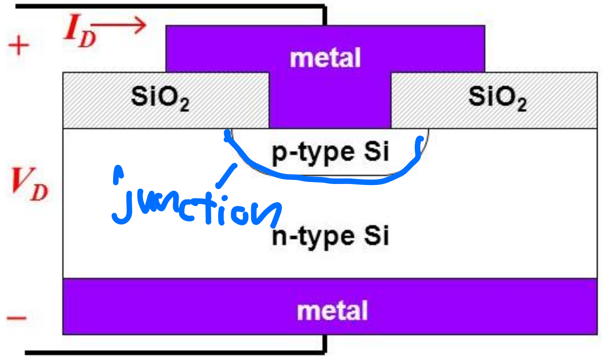
Sources: http://ece-research.unm.edu/jimp/vlsiII/slides/html/diode1.html

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

- Junction = boundary or interface between two types of materials. Examples:
  - p-n
  - n-n
  - p-p
  - p^+-n
  - n^+-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)

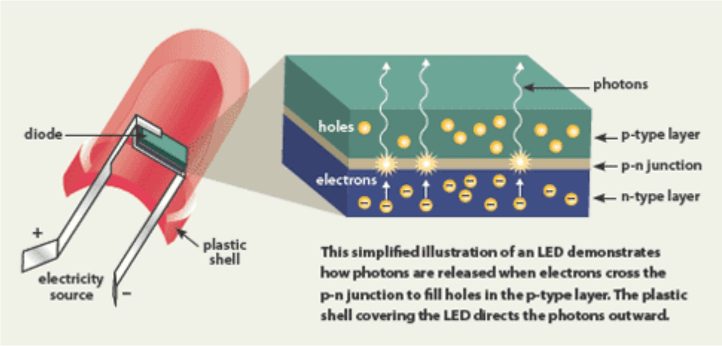
For simplicity, assume that the doping profile changes abruptly at the junction.



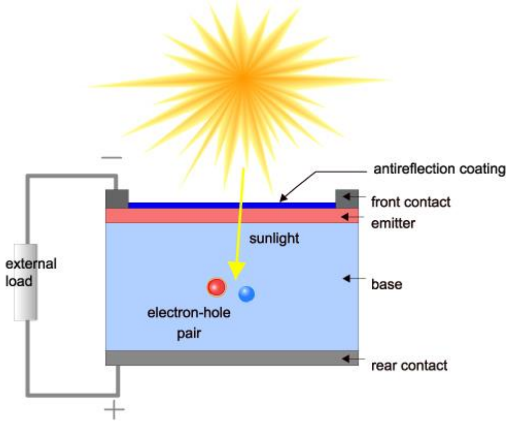
Sources: https://slideplayer.com/slide/6958660/

p-n Diode: Applications

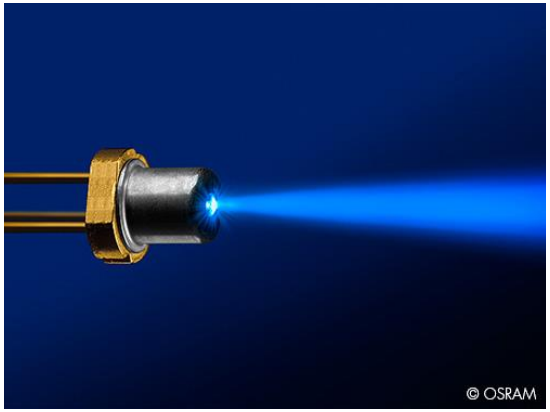
LEDs

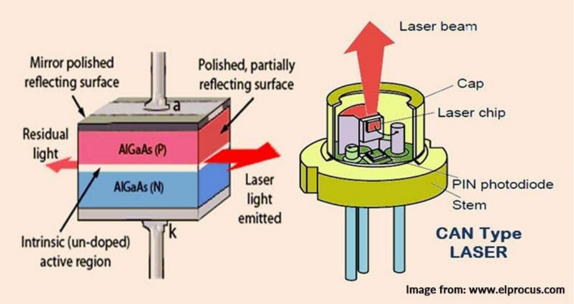


Solar cells



Laser Diodes





Sources: UPS Battery Center, Wikipedia, Electronics Hub, Electron Test Equipment, Laser Components, PV Education

Current Flow: Qualitative description

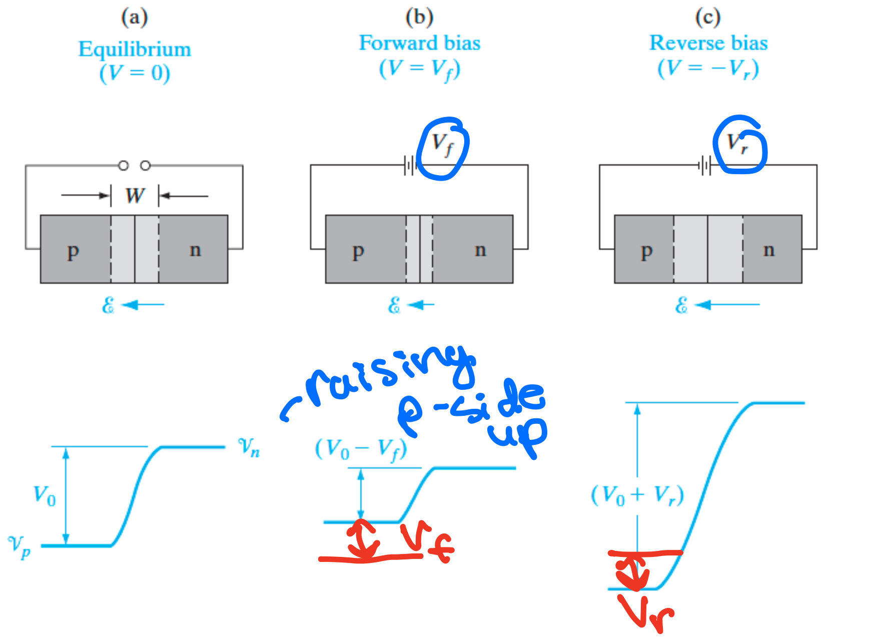
- What happens when we leave equilibrium and apply an external bias (V)?
  - Recall: Net current flow in equilibrium is 0
    Only E-field is the built-in field
- Assumption: V appears across entirely across W and not in the quasi-neutral regions
  - Is this actually the case? No, but voltage drop is low
    Doping is heavy → R is low (V=IR)
- 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

Sources: Textbook

Bias effects on Electrostatic Potential Barrier

- Forward bias, ($V = V_f$) is a +V --> bias is positive on the p-side relative to the n-side
- Reverse bias, ($V = -V_r$) is a -V --> bias is negative on the p-side relative to the n-side

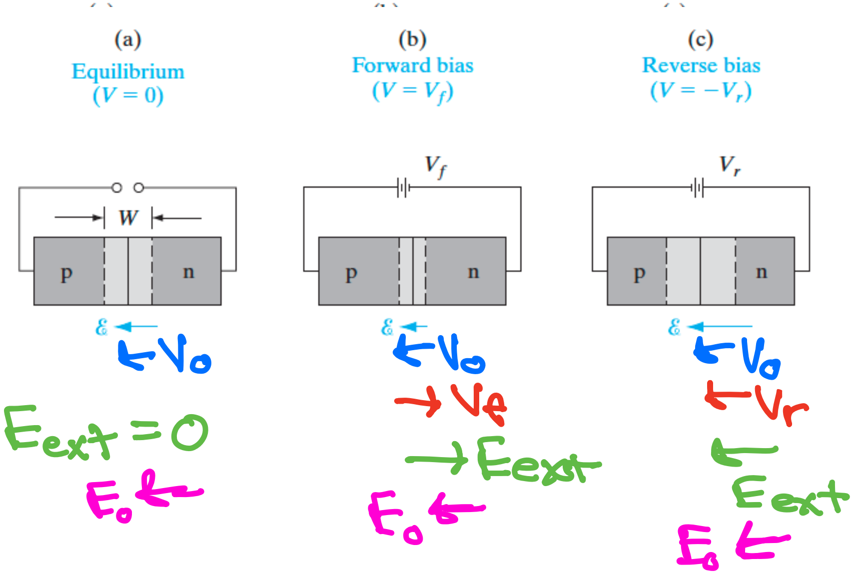


- Electrostatic potential barrier:
  - Forward bias: Lowers potential barriers (p positive with respect to n) and raises the electrostatic potential on p-side
  - Reverse bias: The opposite occurs! Electrostatic potential of the p-side is depressed relative to the n-side, and potential barrier at junction becomes larger

Sources: Textbook

Bias effects on Electric Field

- Now we have two E-field components to consider
  - Applied arises from Vexternal
  - Built-in arises from charge neutrality, V_0
- 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

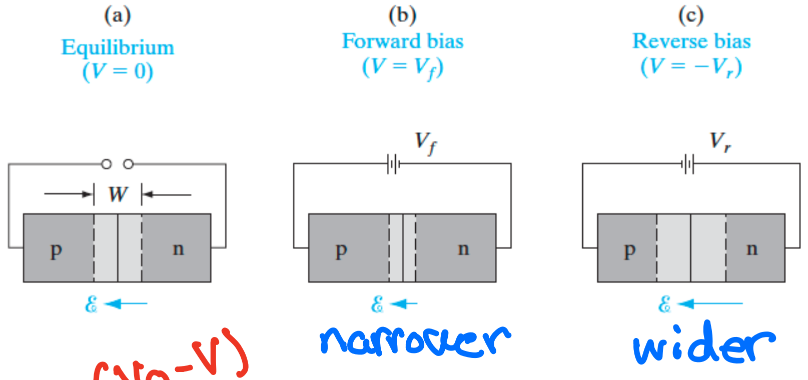
Sources: Textbook

Bias effects on Transition Region Width

- Recall: W varies with the $\sqrt{|V|}$

- 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_{p_0}, x_{n_0} if we replace V_0 by the new barrier height, $V_0 - V$



$(V_0 - V)$

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

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

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

be careful w/ sign in forward and reverse bias

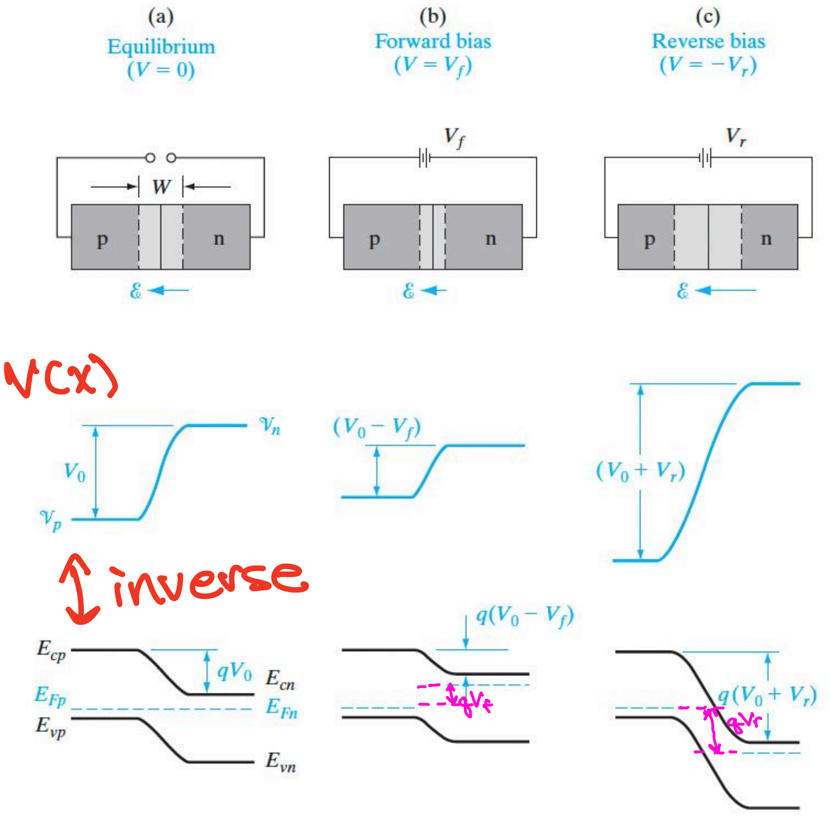
Sources: Textbook

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 E_{Fp} and E_{Fn} in the two QNRs are separated by an energy equal to qV

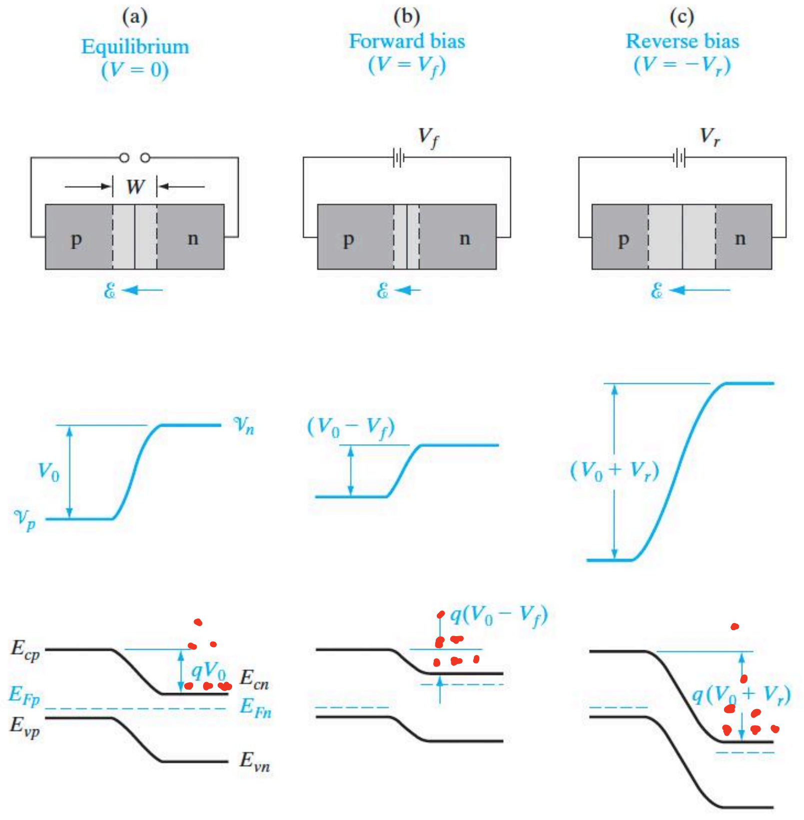
- Forward bias: Separation **decreases** by compared to equilibrium and is $q(V_0 - V_f)$
- Reverse bias: Separation **increases** by compared to equilibrium and is $q(V_0 + V_r)$ units: eV



Sources: Textbook

Bias effects on Diffusion Current

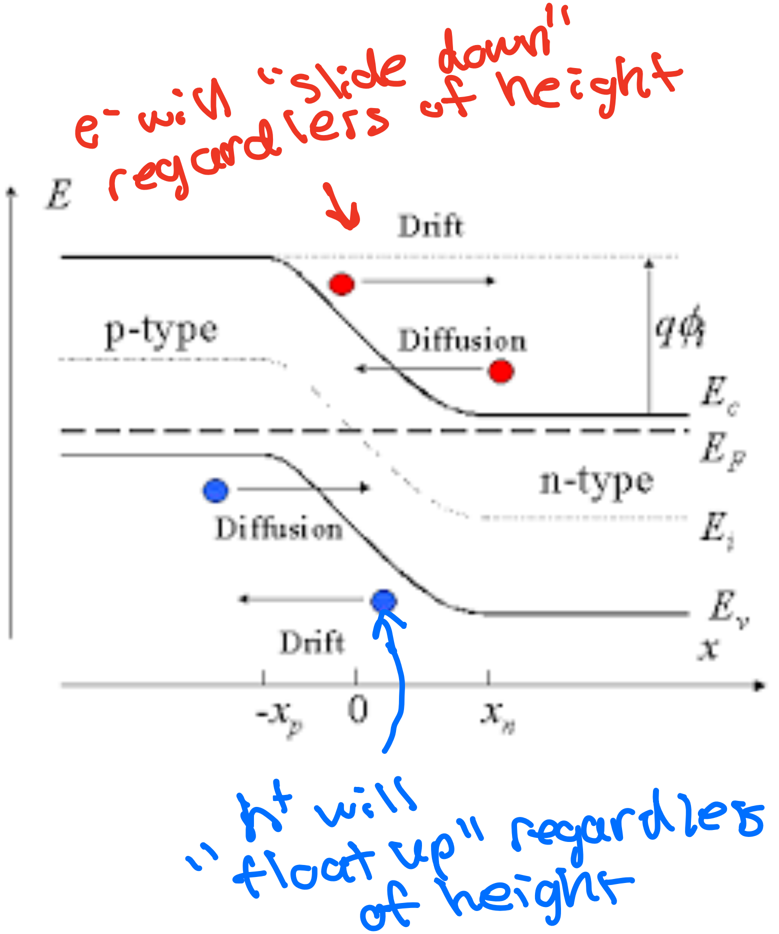
- Recall:
  - Diffusion of majority h+ on p-side to n-side
  - Diffusion of majority e- on n-side to p-side
- Both carriers have to surmount the potential energy barrier
- Equilibrium: some e- and h+ have enough energy to diffuse across barrier
- Forward bias: Barrier is lower, so more e- and h+ can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



Sources: Textbook

Bias effects on Drift Current

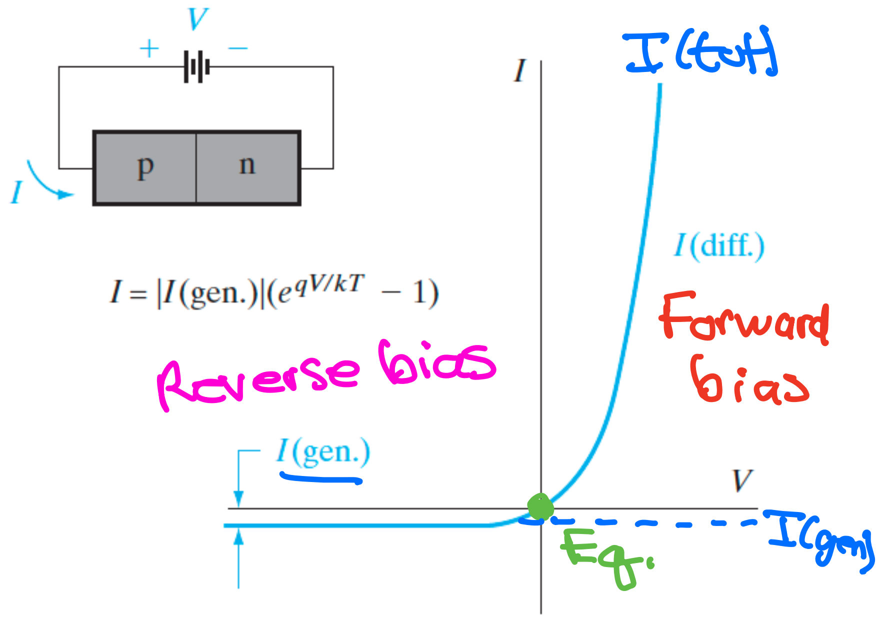
- Relative insensitive to the height of the potential barrier
- The electron and hole drift currents at the junction are **independent** of applied volage
- Why?
- Drift current is limited by how often carriers are swept down the barrier
- Imagine: Every minority e- on the p-side which wanders into the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



Sources: UCSC Course Review

Generation Current

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



Sources: Textbook

Total Currents Across the Junction

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

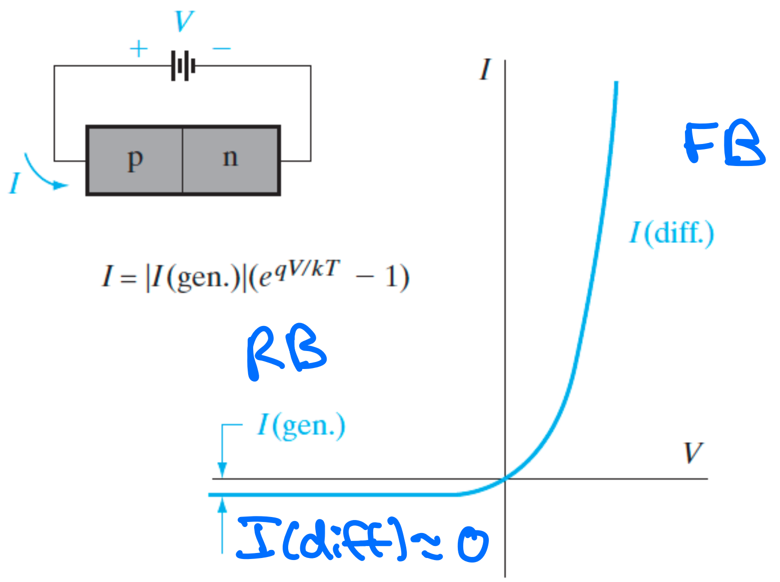
From left to right on diagram:

- Reverse bias: barrier to diffusion is large so diffusion currents are negligible. Only current is a relatively small, generation current I(gen) which is due to minority carrier drift
  ↑ same as I_0

- 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!**

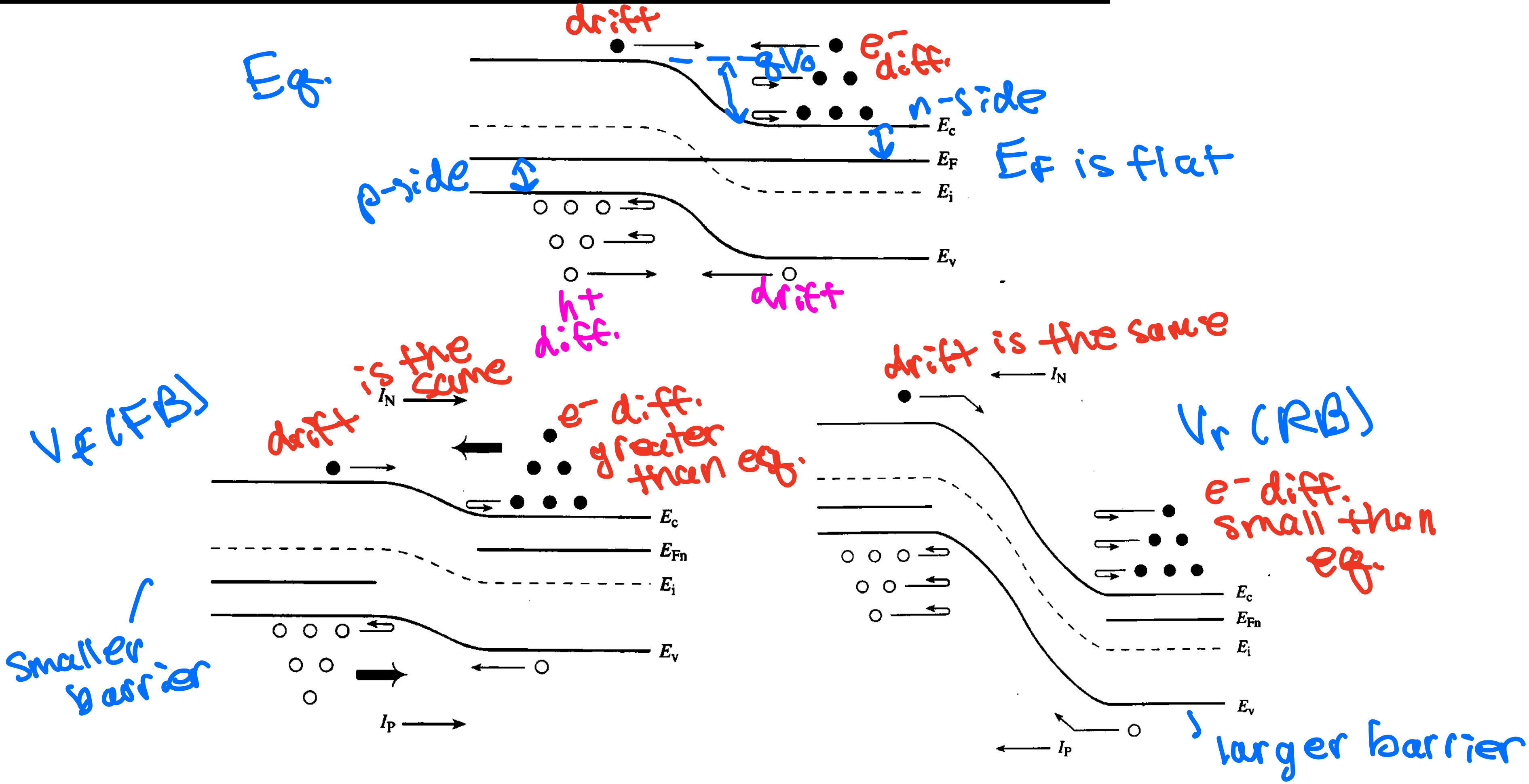


$$I = I(\text{diff.}) - |I(\text{gen.})| = 0 \text{ for } V = 0$$

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

Sources: Textbook

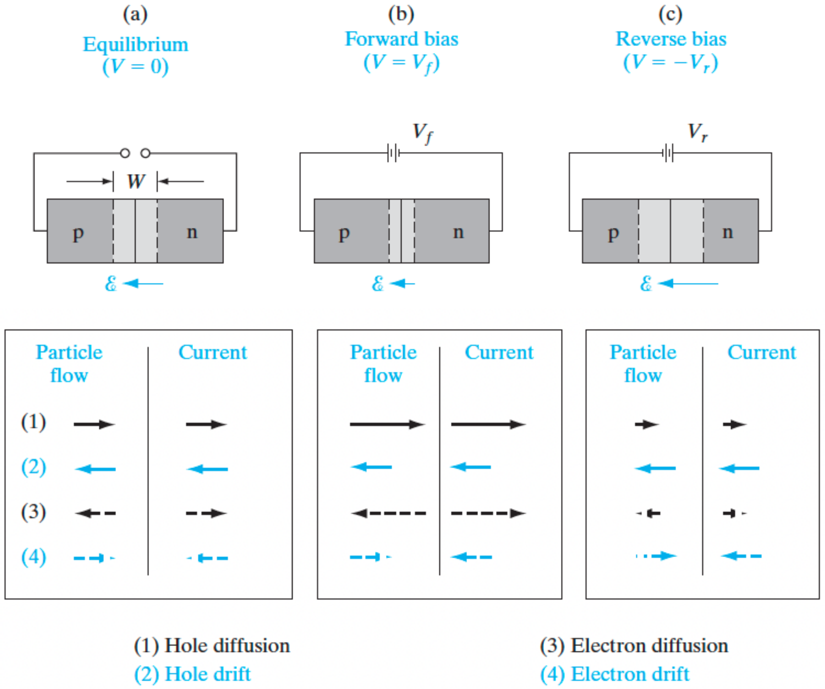
Visualizing Directions of Particle and Current Flow



Sources: E. Pop ECE 340 Slides

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



Sources: Textbook

Minority Carrier Injection in Forward Bias

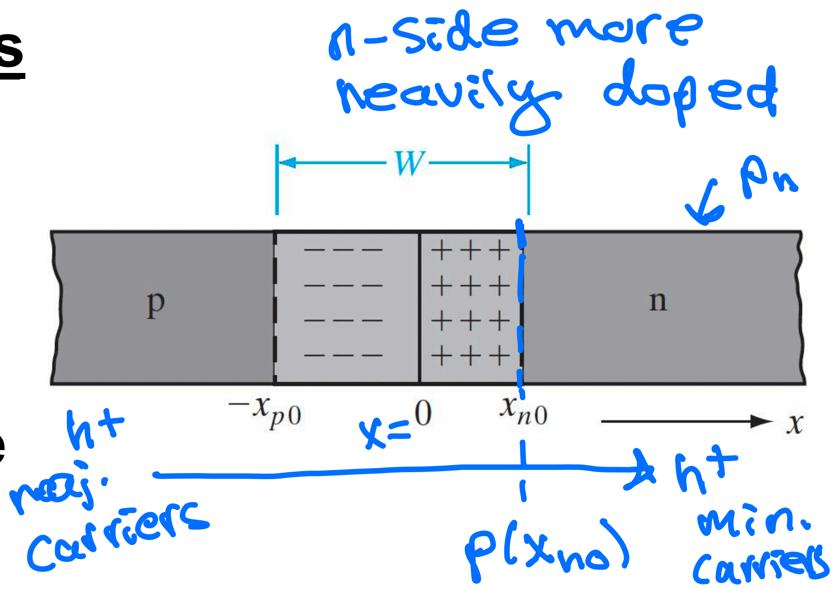
- Recall: For low-level injection, we can neglect changes in majority carrier concentration

- As we apply forward bias, we increase the minority carrier concentration:

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

# of holes on n-side in QNR

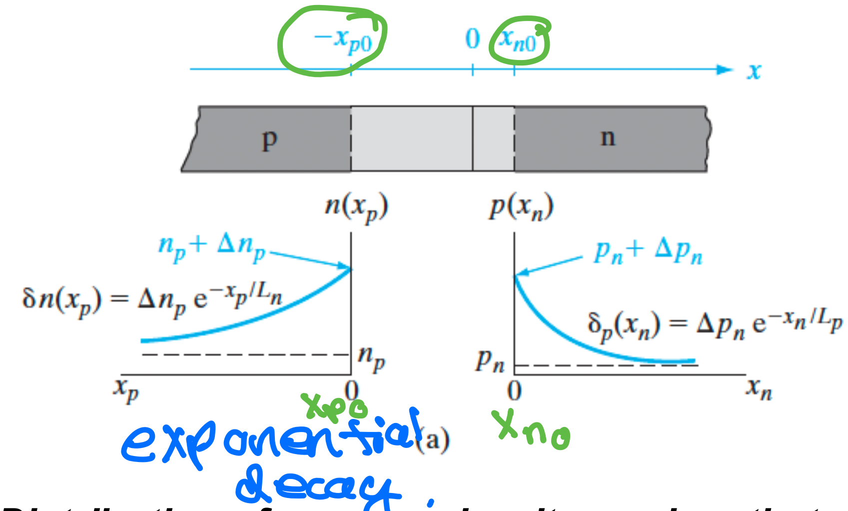
- Conversely, $p(x_{n_0})$ is decreased below equilibrium value p_n in reverse bias



Sources: Textbook

Excess Minority Carrier Spatial Distributions

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



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

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

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

Sources: Textbook

The Ideal Diode Equation

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

gradient

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

- Total __h^+__ 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 __e^-__ 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)

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

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

Sources: Textbook

Reverse Saturation Current

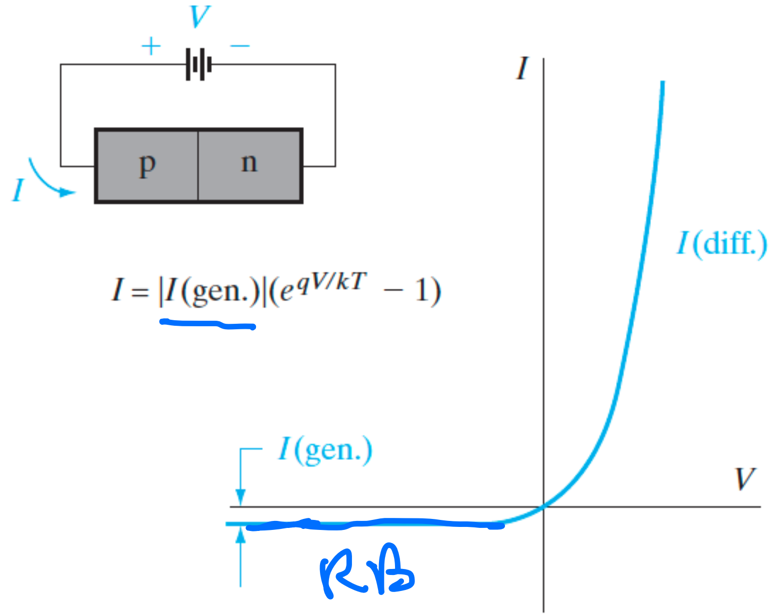
- Denoted I_0 (J_0 A/cm^2)
  - Units: A

$I_0 = |I_{gen}|$

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

- Holds as long as V_r is larger than a few kT/q $\approx$ 26 mV

- Equal to the absolute value of I_{gen}



Sources: Textbook

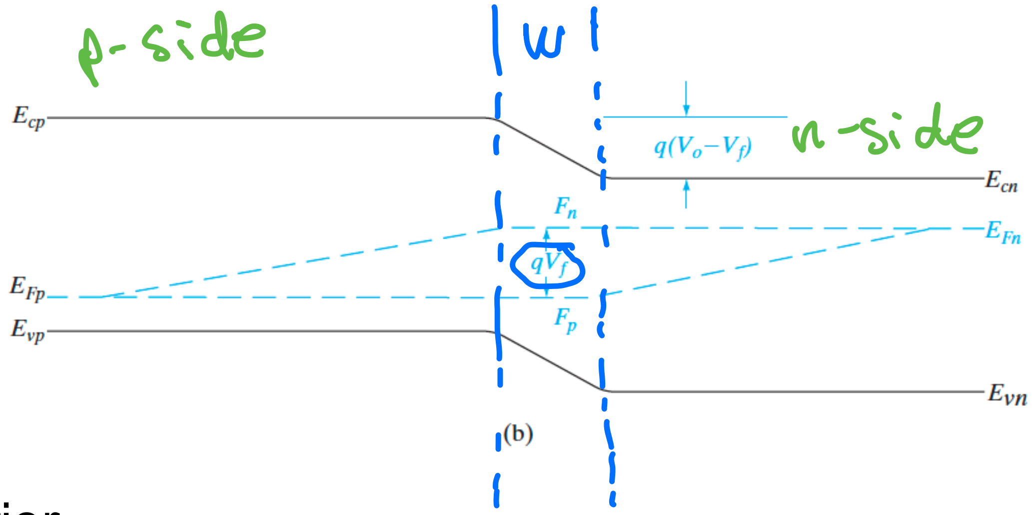
Energy Band Diagram: Forward Bias

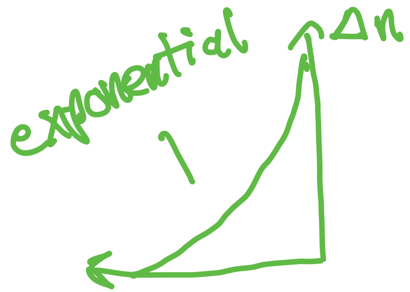
- E_F splits into quasi-Fermi levels

  depletion region

- Within W, they are separated by qV_F (or qV_r)

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





- 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

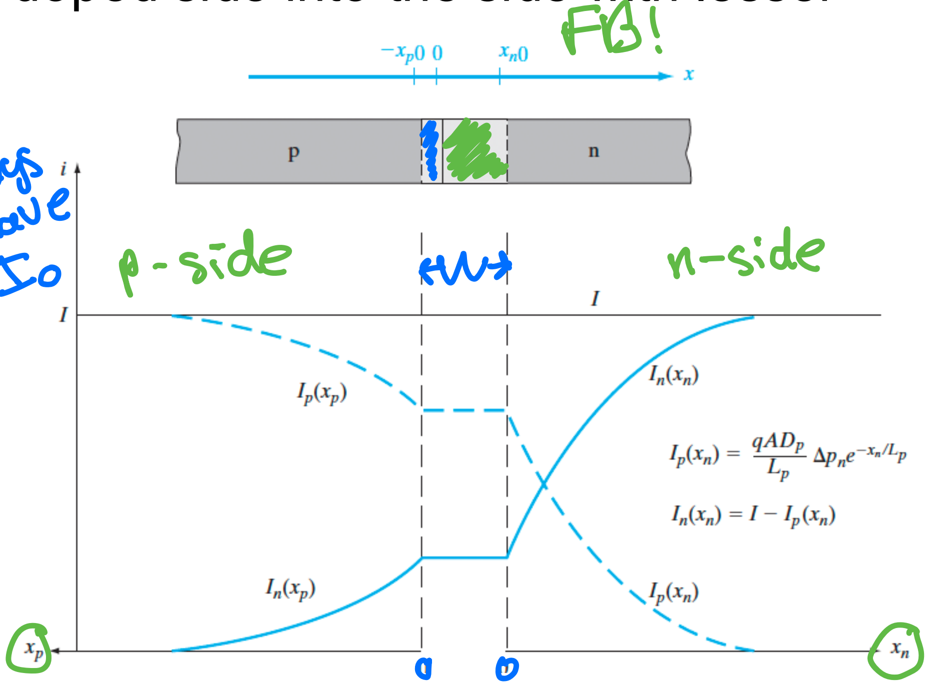
Sources: Textbook

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

- Which side has higher doping? p-side (we can tell from $x_{p0} < x_{n0}$)
- 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.

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

always have I_0

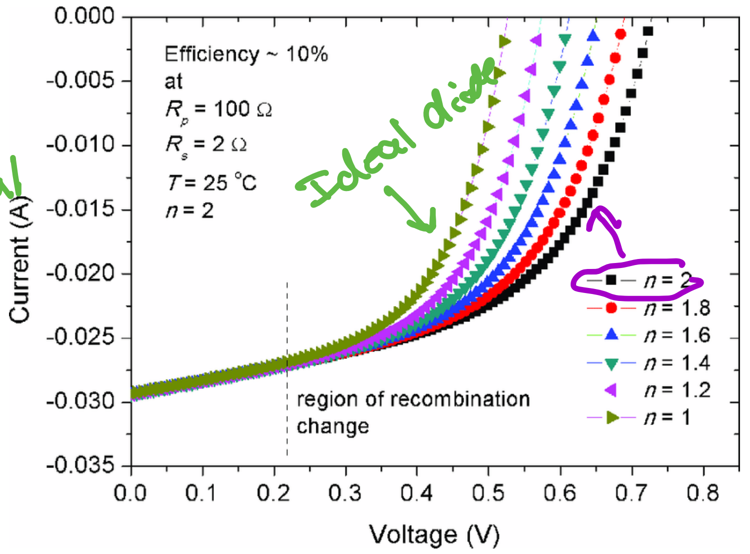


Sources: Textbook

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 proportional to ni and increases exponentially with forward bias
- We can capture this effect by modifying the ideal diode equation:

$$I = I'_0(e^{qV/\mathbf{n}kT} - 1)$$



- Where n___ is the ideality factor and varies between 1 and 2
- What does n depend on? Material_____________ and temperature_____________

Sources: Textbook

Reverse Bias and Minority Carrier Extraction

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

$$\Delta n_p \simeq -n_p.$$

- From our earlier discussion, RB
  - E-field across W increases
  - Current is due only to minority carrier drift across the junction
  - Current is supplied by EHP generation in the SCR
    ↑ thermal
- Recall, reverse saturation current:

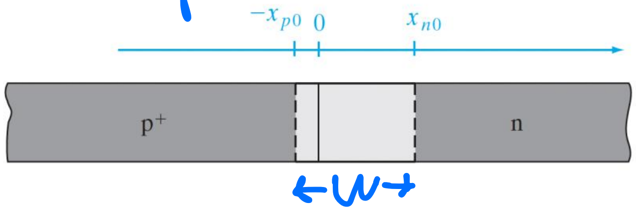
$$I = -qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right) = -I_0$$

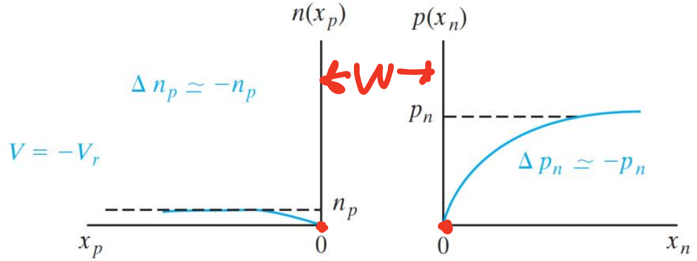
- The same excess carrier distributions from earlier can be used, with $V = -V_r$, and we find:

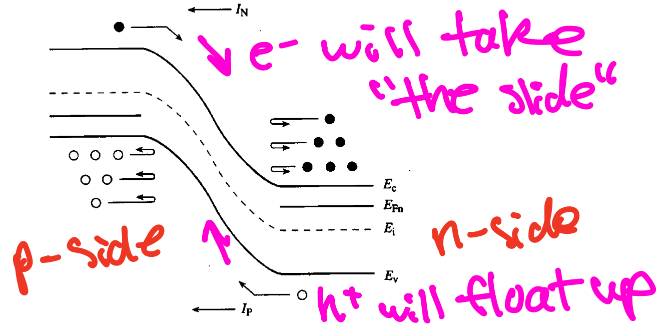
$p_n = 0$ at the edge of W in RB

- Minority carrier concentration at each edge of W becomes 0
- 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

p+-n diode







Sources: E. Pop ECE 240 Slide

Junction (Depletion) Capacitance

$C = \frac{Q}{V}$ in capacitor

- 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?

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

junction capacitance

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

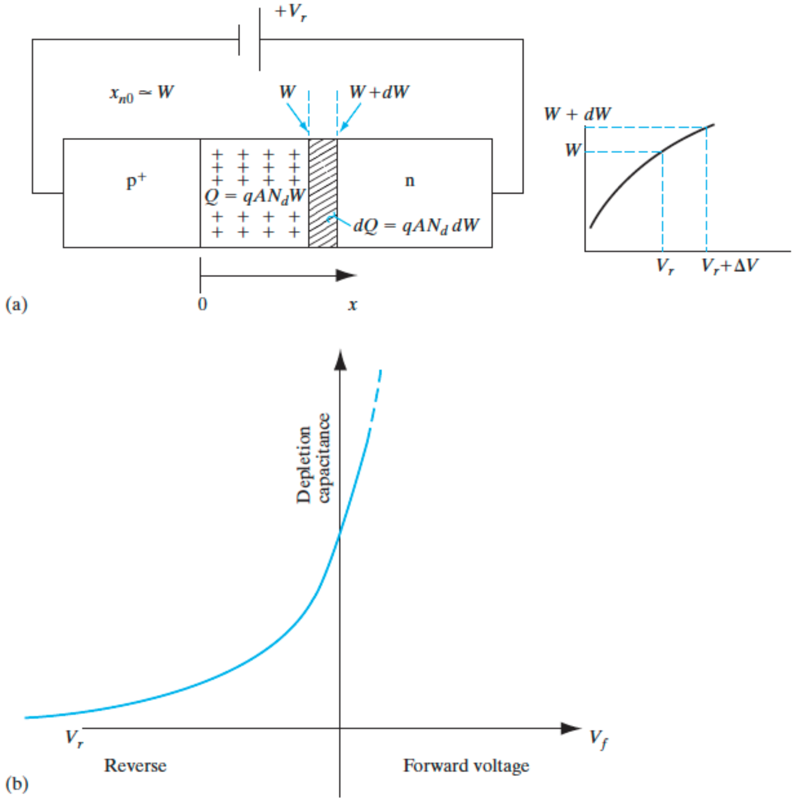
built-in potential

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

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

$\epsilon = \epsilon_0 \epsilon_r$ permittivity

$\epsilon_{Si} = 11.8$ $\epsilon_0 = 8.85 \times 10^{-14}$ F/cm



Sources: Textbook, E. Pop ECE 240 Slide

Junction Capacitance in Asymmetric Junctions

p^+-n or p-n^+

- What about in an asymmetrically doped diode?

Abrupt (not graded), doping is very different on p and n sides

For p^+-n,

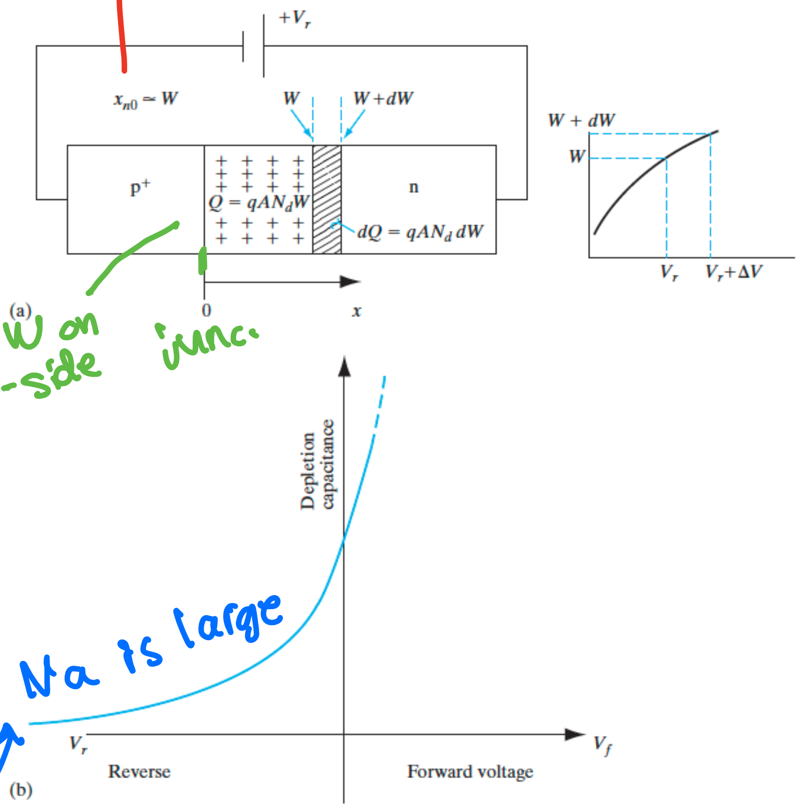
- W extends primarily into n-side
- x_{p0} is negligible
- $N_a \gg N_d$

(p-side, n-side)

- Capacitance is determined by only ONE of the doping concentrations

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

N_a for p-n^+



No W on p+-side
junc.
Na is large
$\frac{1}{N_a} + \frac{1}{N_d}$ in previous slide

Sources: Textbook

Measuring Junction Capacitance

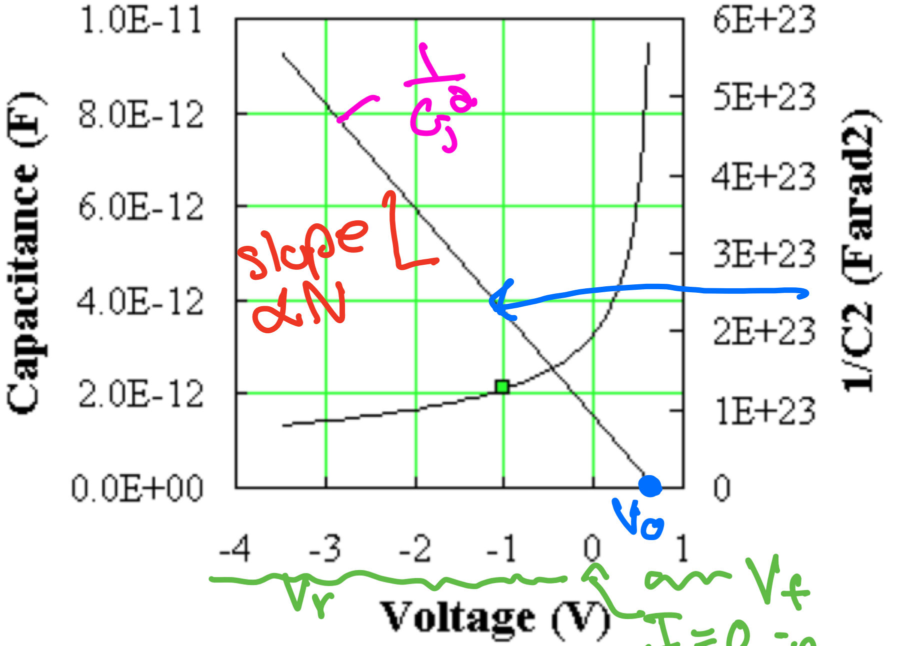
- So, if we measure and plot $\frac{1}{C_j^2}$ vs V, we can get the doping concentration
- On the more lightly doped side of an asymmetric junction

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

mx + b

↑ more lightly doped (either N_a or N_d)

- Slope = $\frac{2}{A^2 q \varepsilon_s N}$
- We can also find the built-in potential
  - $V_0 = \frac{kT}{q}\ln\left(\frac{N_a N_d}{n_i^2}\right)$



Sources: E. Pop ECE 240 Slide

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 relative to Eq.
  - Excess of carriers compared to equilibrium (injection)
- Reverse bias:
  - Almost no current flows
  - More reverse bias means a broader depletion region
  - Reverse saturation current (I_0 = $|I_{gen}|$) 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

Sources: Textbook

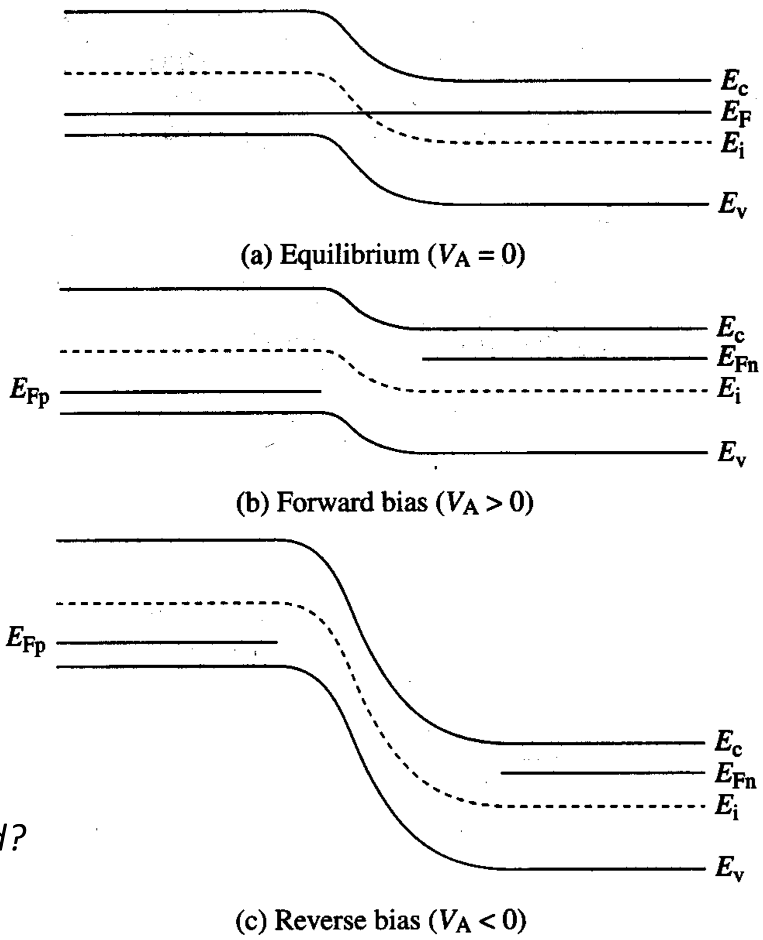
Visual Summary

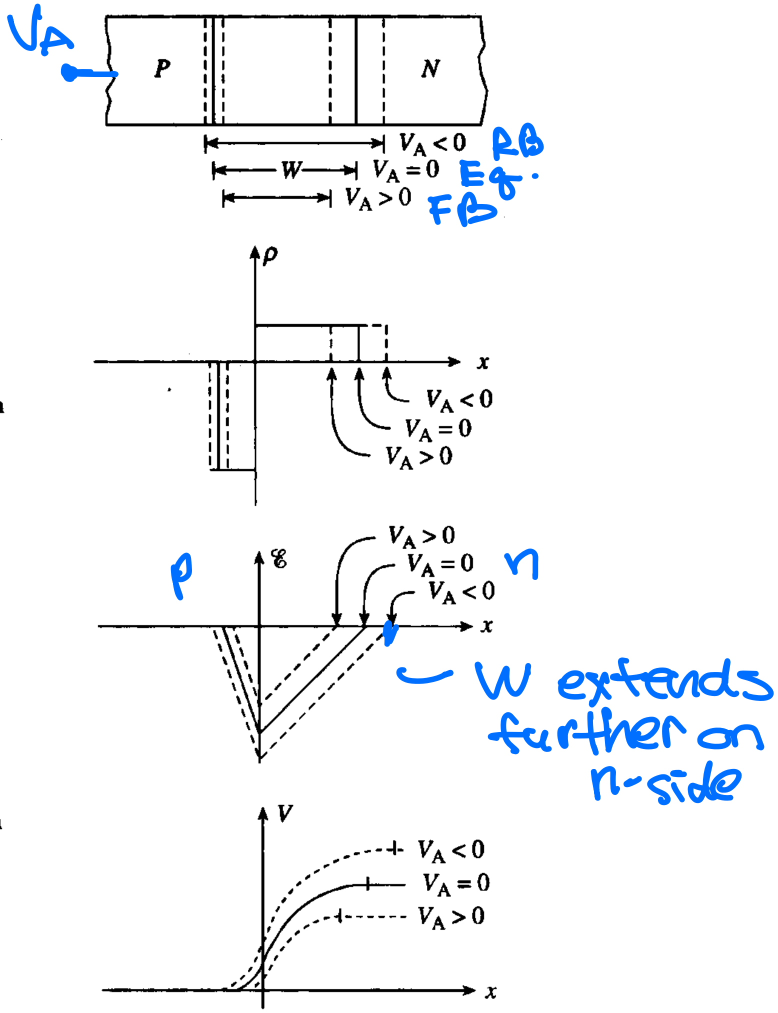
Equilibrium
(V = 0)

Forward bias

(V > 0)

Reverse bias
(V < 0)





Which side more lightly doped?

n-side

Sources: E. Pop ECE 340 Slides