Chapter 5: Junctions and Diodes

ELEC 424
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Abrupt pn Junctions

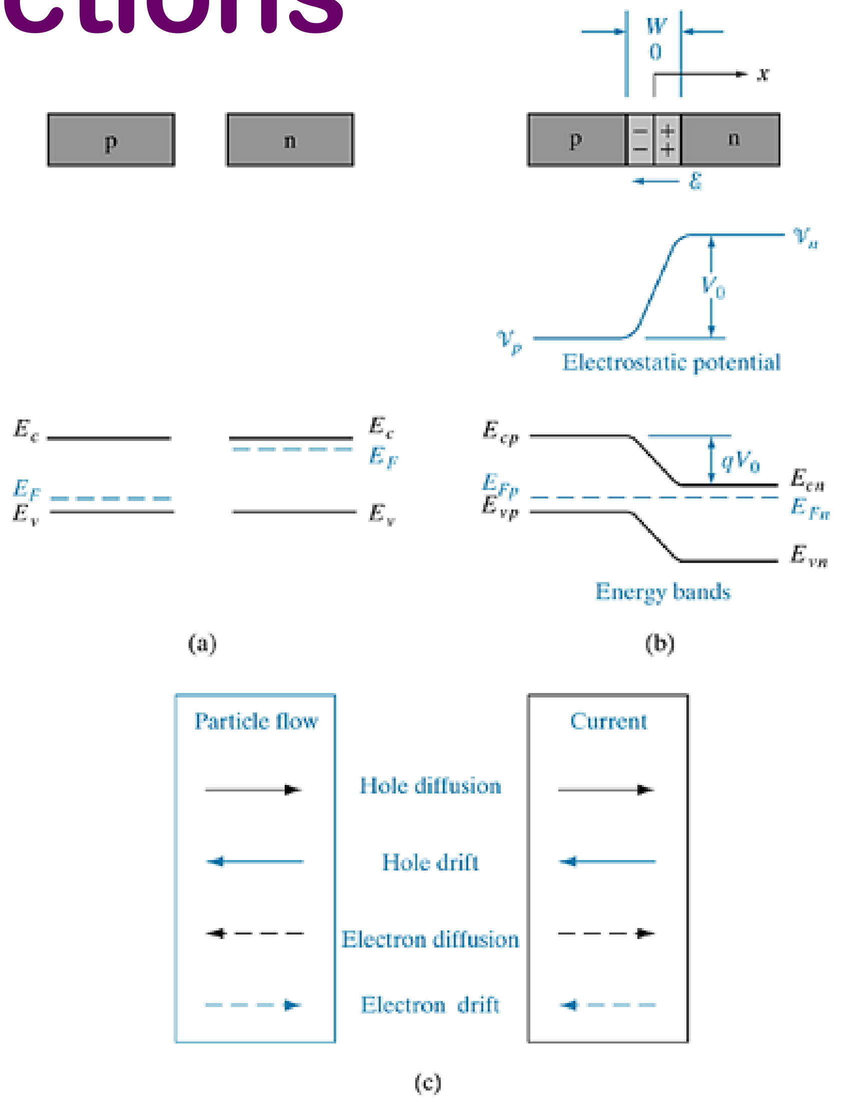
e^- move from n to p regions.

Donors and acceptors are ionized.

Fermi levels align.

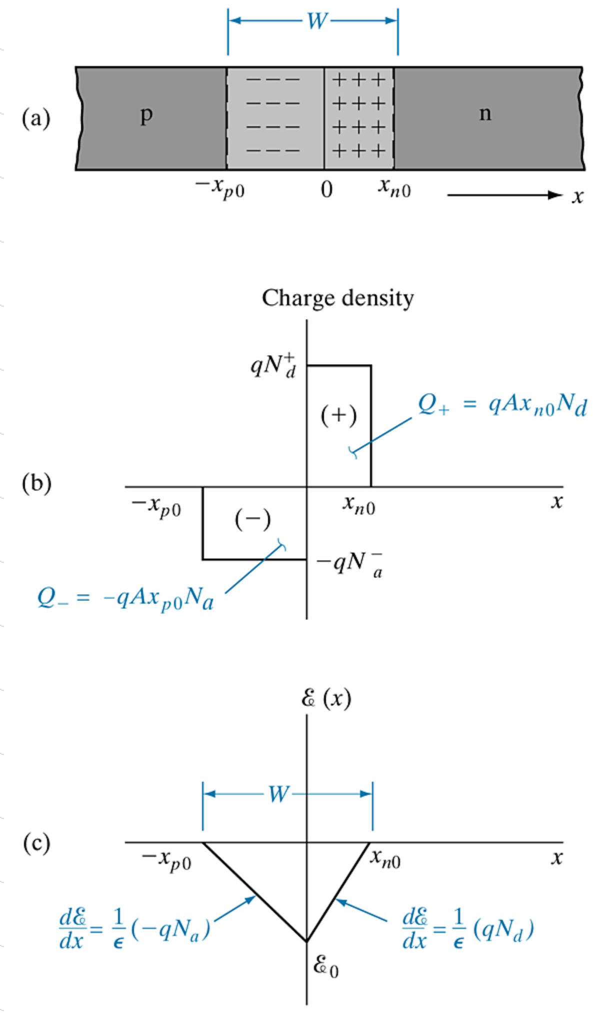
“Built-in” electric field limits charge flow.

An area of “depleted” donors results.



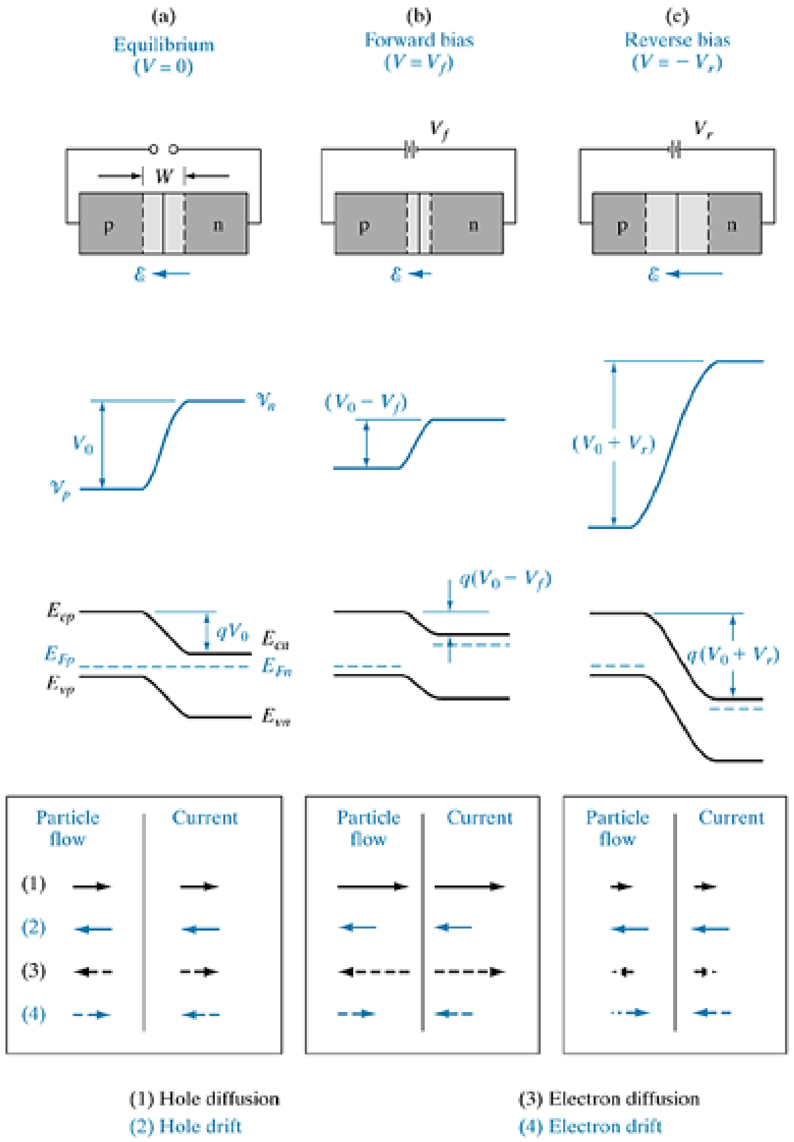
Space Charge Neutrality

- Positive and negative charge in the depleted regions must balance.
- Depletion extends further into the more lightly doped side of the junction.
- The electric field is zero at the edges of the depletion region and is maximum at the junction.

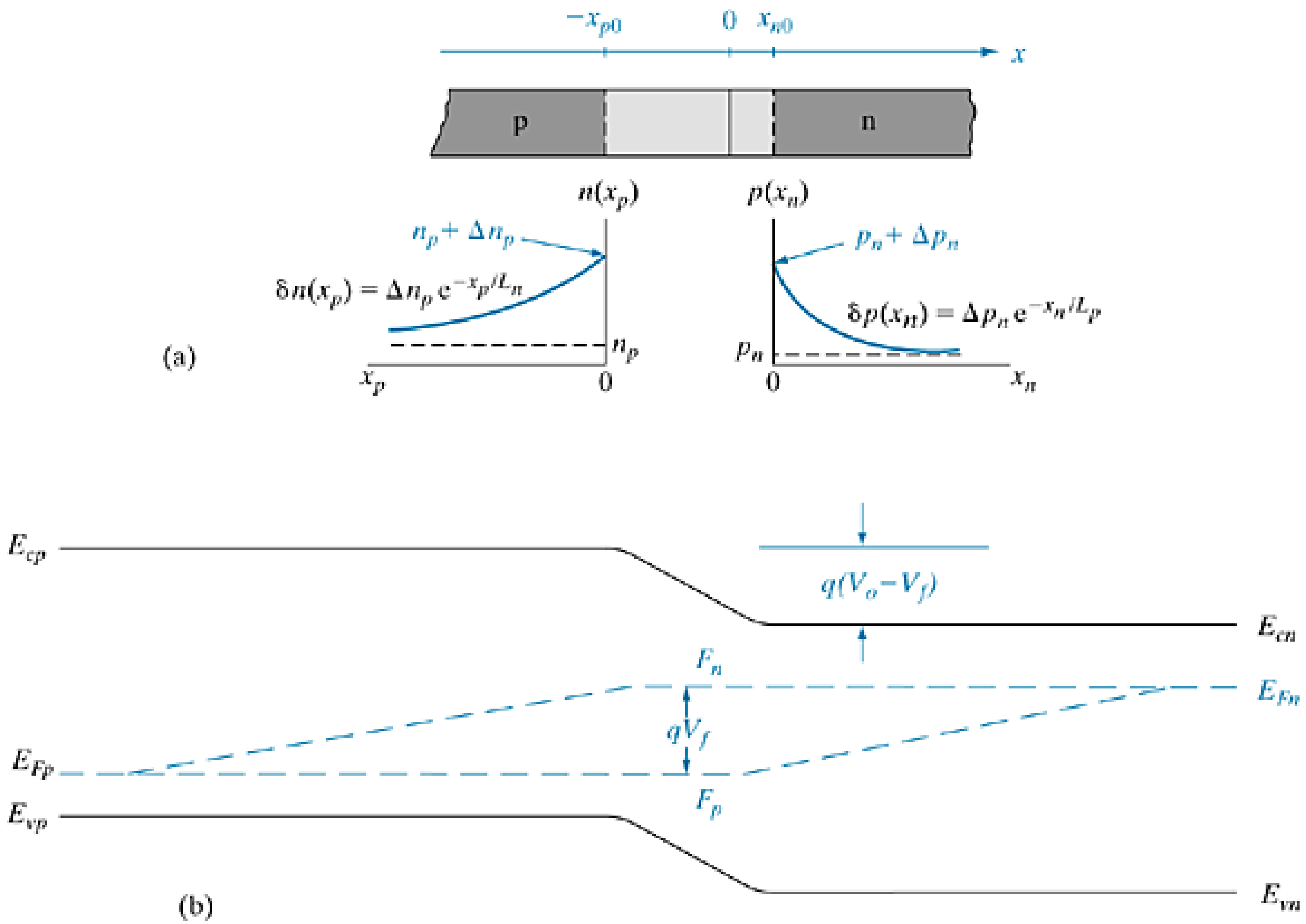


Diffusion and Drift Currents

- Current and particle components balance out at zero bias.
- Forward bias narrows the depletion region and lowers the built-in voltage, allowing marked increase in diffusion current components.
- Reverse bias widens the depletion region and raises the built-in voltage barrier, throttling diffusion currents.



Forward Biased Junctions



Forward-biased junction: (a) minority carrier distributions on the two sides of the transition region and definitions of distances x_n and x_p measured from the transition region edges; (b) variation of the quasi-Fermi levels with position.

Things to Remember about Junctions

- At zero bias the Fermi level is constant

$$qV_o = E_{F_p} - E_{F_n}$$

- The junction dipole must be space charge neutral

$$Q^+ = \left|Q^-\right|$$

- Poisson's equation relates the *E*-field gradient to local space charge at any point

$$\frac{d\xi(x)}{dx} = \frac{q}{\varepsilon}\left(p - n + N_d^+ - N_a^-\right)$$

From $\frac{d\xi(x)}{dx} = \frac{q}{\varepsilon}\left(p - n + N_d^+ - N_a^-\right)$

- Neglecting $p - n$ as small compared to dopant concentrations and because all dopants are ionized at 300K

$$\frac{d\xi(x)}{dx} = \frac{q}{\varepsilon}\left(N_d - N_a\right)$$

or $$\left.\frac{d\xi(x)}{dx}\right|_{n-side} = \frac{q}{\varepsilon}\left(N_d\right) \Rightarrow \xi_o = -\frac{q}{\varepsilon} N_d x_{no}$$

and $$\left.\frac{d\xi(x)}{dx}\right|_{p-side} = -\frac{q}{\varepsilon}\left(N_a\right) \Rightarrow \xi_o = -\frac{q}{\varepsilon} N_a x_{po}$$

$-\frac{q}{\varepsilon} N_a x_{po}$ *is the E-field maximum value*

Potential and Width

- Can we calculate the built-in (contact) potential and width of the depletion (transition) region?

$$\xi(x) = \frac{dV_o}{dx}$$

$$V_o = \int_{-x_{po}}^{x_{no}} \xi(x)dx = \frac{1}{2}\xi_o W \qquad \textit{where} \qquad W = x_{no} + x_{po}$$

thus $$V_o = \frac{1}{2}\frac{q}{\varepsilon}N_d x_{no} W$$

The portion of W on either side of the junction is *<u>inversely</u>* *proportional to the dopant concentration or*

$$x_{no} = W\left(\frac{N_a}{N_a + N_d}\right) \qquad \textit{so} \qquad V_o = \frac{1}{2}\frac{q}{\varepsilon}\left(\frac{N_d N_a}{N_a + N_d}\right)W^2$$

Potential and Width

- Solving for W

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

or

$$W = \left[\frac{2\varepsilon kT}{q^2}\left(\ln \frac{N_a N_d}{n_i^2}\right)\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{\frac{1}{2}}$$

In terms of doping concentration only (no V_o)

EXAMPLES 5-1 and 5-2

EXAMPLE 5-1

Abrupt PN junction with $N_a = 10^{18} cm^{-3}$ and $N_d = 5X10^{15} cm^{-3}$, 300K

1. Fermi Level:

$$E_{ip} - E_F = kT \ln \frac{p_p}{n_i} = 0.0259 \ln \frac{10^{18}}{1.5x10^{10}} = 0.467eV$$

$$E_F - E_{in} = kT \ln \frac{n_n}{n_i} = 0.0259 \ln \frac{5x10^{15}}{1.5x10^{10}} = 0.329eV$$

2. Built in Potential: If you have both above, just add them,

$$qV_0 = 0.467 + 0.329 = 0.796eV$$

Or you can calculate it directly with the N_a and N_d values.

$$qV_0 = kT \ln \frac{N_a N_d}{n_i^2} = 0.0259 \ln \frac{5x10^{33}}{2.25x10^{20}} = 0.769eV$$

EXAMPLE 5-2

Calculate the depletion region characteristics for the given junction of area $\pi r^2 = 7.85\times 10^{-7} cm^2$, given its radius of 10*μm* .

1. We calculated contact potential in example 5-1, and can use $W = \left[\frac{2\varepsilon V_o}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)\right]^{\frac{1}{2}}$ to calculate that *W* = 0.457*μm*.

   Remember $\varepsilon = \varepsilon_{Si}\times\varepsilon_o = (11.8)(8.85\times 10^{10})$

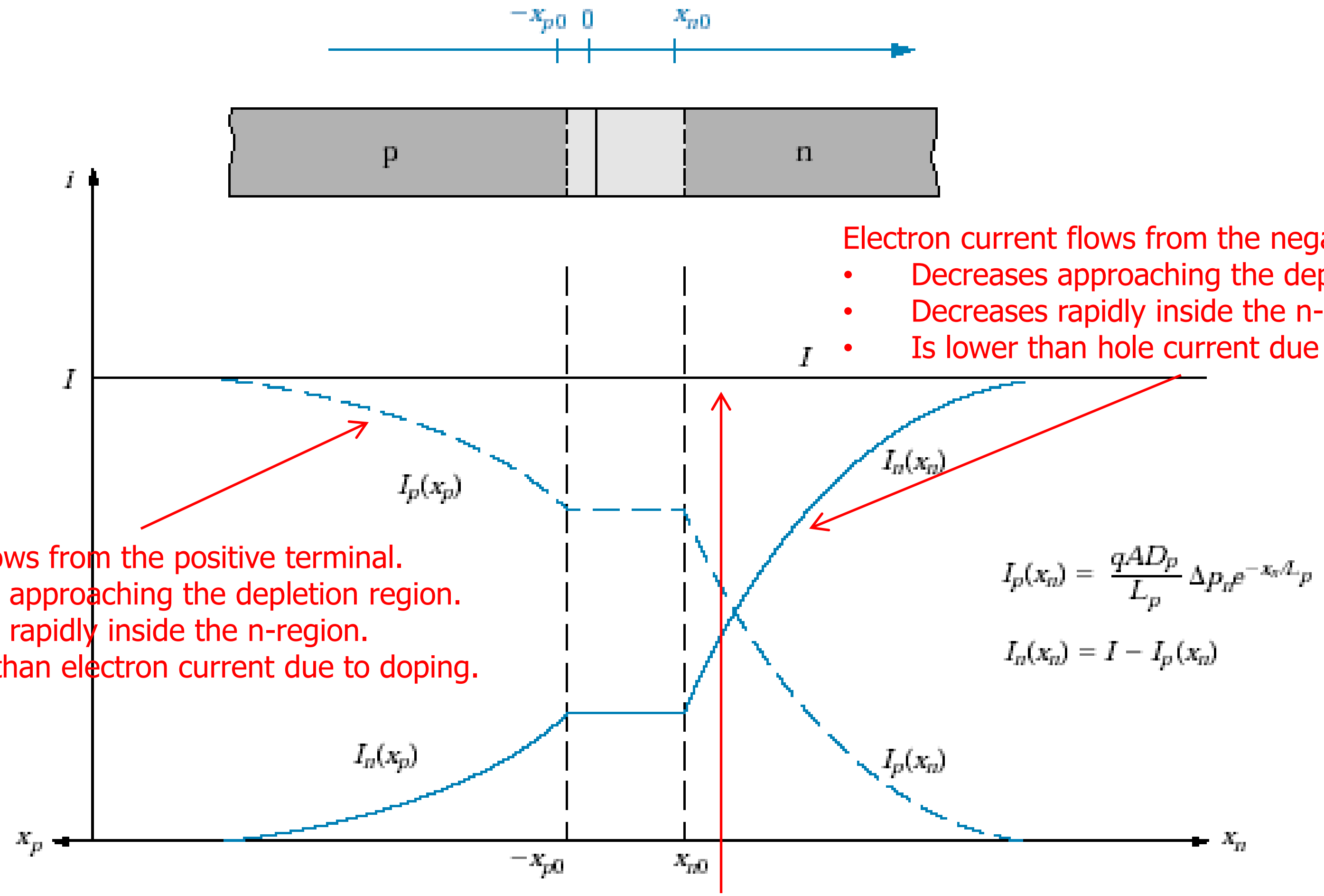
2. The depletion region, *W* extends into each side of the junction depending on the ratio of doping concentrations.

$$x_{no} = W\left(\frac{N_a}{N_a+N_d}\right) = \frac{W}{1+\frac{N_d}{N_a}}$$

   Because N_a is 200 times N_d the depletion region extends nearly all of its width into the *n*-type side of the junction, making x_{no}=.455 *μm and* x_{po}*=0.002 μm.*

3. Use x_{no} to calculate $Q^+ = qAx_{n_o}N_d$ and $\xi_o - \dfrac{q}{\varepsilon}N_d x_{n_o}$.

Carrier Injection (Forward Bias)



Electron current flows from the negative terminal.
- Decreases approaching the depletion region.
- Decreases rapidly inside the n-region.
- Is lower than hole current due to doping.

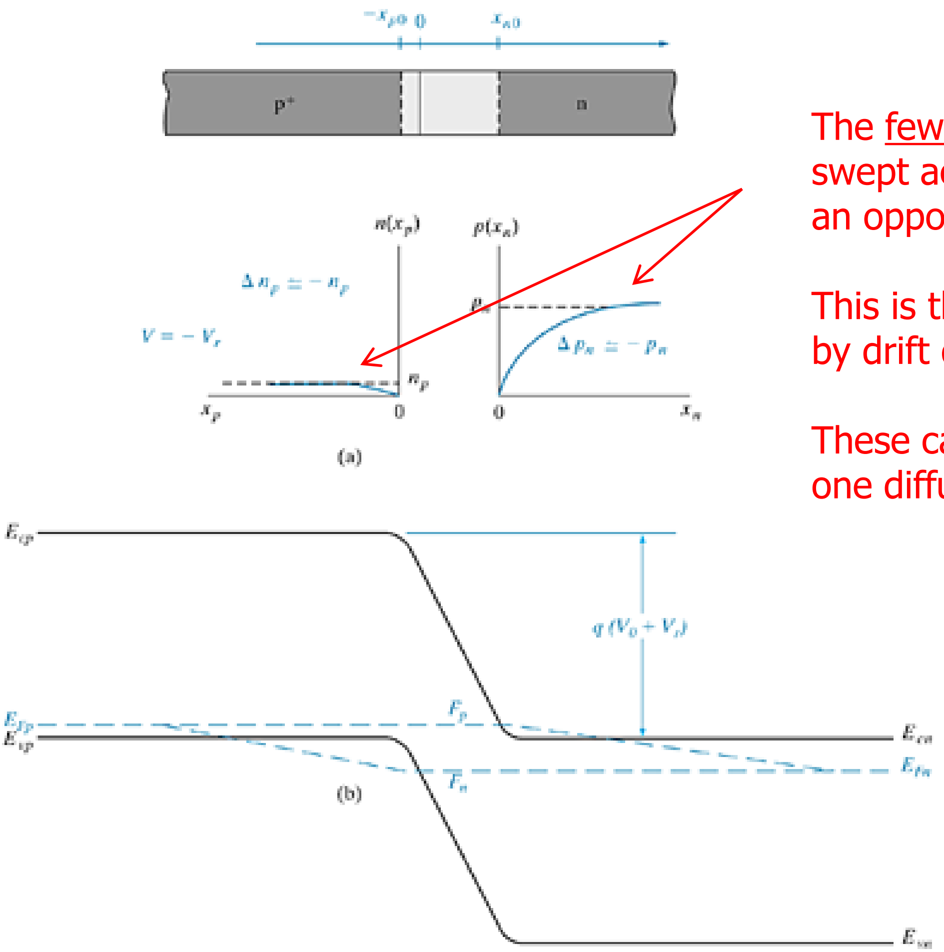
$$I_p(x_n) = \frac{qAD_p}{L_p}\Delta p_n e^{-x_n/L_p}$$

$$I_n(x_n) = I - I_p(x_n)$$

Hole current flows from the positive terminal.
- Decreases approaching the depletion region.
- Decreases rapidly inside the n-region.
- Is higher than electron current due to doping.

The hole and electron current add to *I* at all points along x.

Reversed Biased Junctions

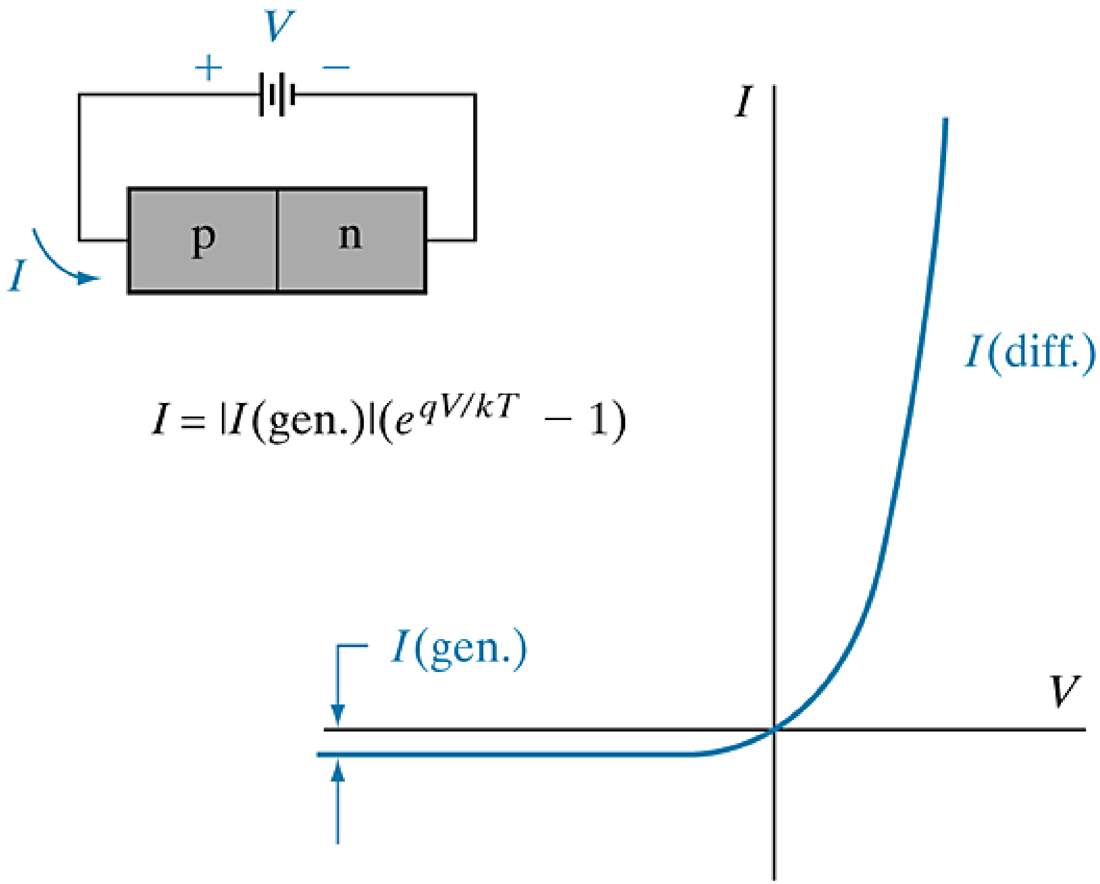


The few minority carriers in each region are swept across the junction but not replaced by an opposing diffusion current.

This is the “reverse saturation” current, caused by drift due to the built-in voltage (or barrier).

These carriers are thermally induced within one diffusion length of the transition region.

I-V Characteristic



Ideal Diode Equation

Calculates the forward and reverse current across an abrupt p-n junction:

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

I_o is the reverse saturation current (often considered "leakage). This makes sense as $-qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)$ sums the current due to minority charge carrier current in both the *n* and *p* side.

D and *L* are the diffusion coefficient and diffusion length for electrons and holes, and are bound by τ, per chapter 4 discussion on p 141 of the text. $L \equiv \sqrt{D\tau}$

Ideal Diode Example

Suppose: Abrupt p-n junction with the following properties:

p Side	n Side
$N_a = 10^{17}\ cm^{-3}$	$N_d = 10^{15}$
$T_n = 0.1\ us$	$T_p = 10\ us$
$u_p = 200\ cm^2/V\text{-}s$	$u_n = 1300$
$u_n = 700$	$u_p = 450$

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

On the n-side

$$p_n = \frac{n_i^2}{n_n} = \frac{(1.5\times 10^{10})^2}{10^{15}} = 2.25\times 10^5 cm^{-3}$$

$$D_p = \frac{kT}{q}\mu_p = 0.0259\times 450 = 11.66 cm^2/s$$

$$L \equiv \sqrt{D\tau} = 1.08\times 10^{-2} cm$$

On the p-side

$$n_p = \frac{n_i^2}{p_p} = \frac{(1.5\times 10^{10})^2}{10^{17}} = 2.25\times 10^3 cm^{-3}$$

$$D_n = \frac{kT}{q}\mu_n = 0.0259\times 700 = 18.13 cm^2/s$$

$$L \equiv \sqrt{D\tau} = 1.35\times 10^{-3} cm$$

Ideal Diode Example (cont.)

What are the forward and reverse currents at V= $\pm$0.5 volts?

p Side	n Side
N_a = 10^{17} cm^{-3}	N_d = 10^{15}
T_n = 0.1 *us*	T_p = 10 *us*
u_p = 200 $cm^2/V\text{-}s$	u_n = 1300
u_n = 700	u_p = 450

First find the I_o, using the *D*s and *L*s from the prior slide.

$$I_o = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right) = 4.37\times10^{-15}\,A$$

Then:

Forward bias current

$$I = I_o\left(e^{qV/kT} - 1\right) = 1.058\times10^{-6}\,A$$

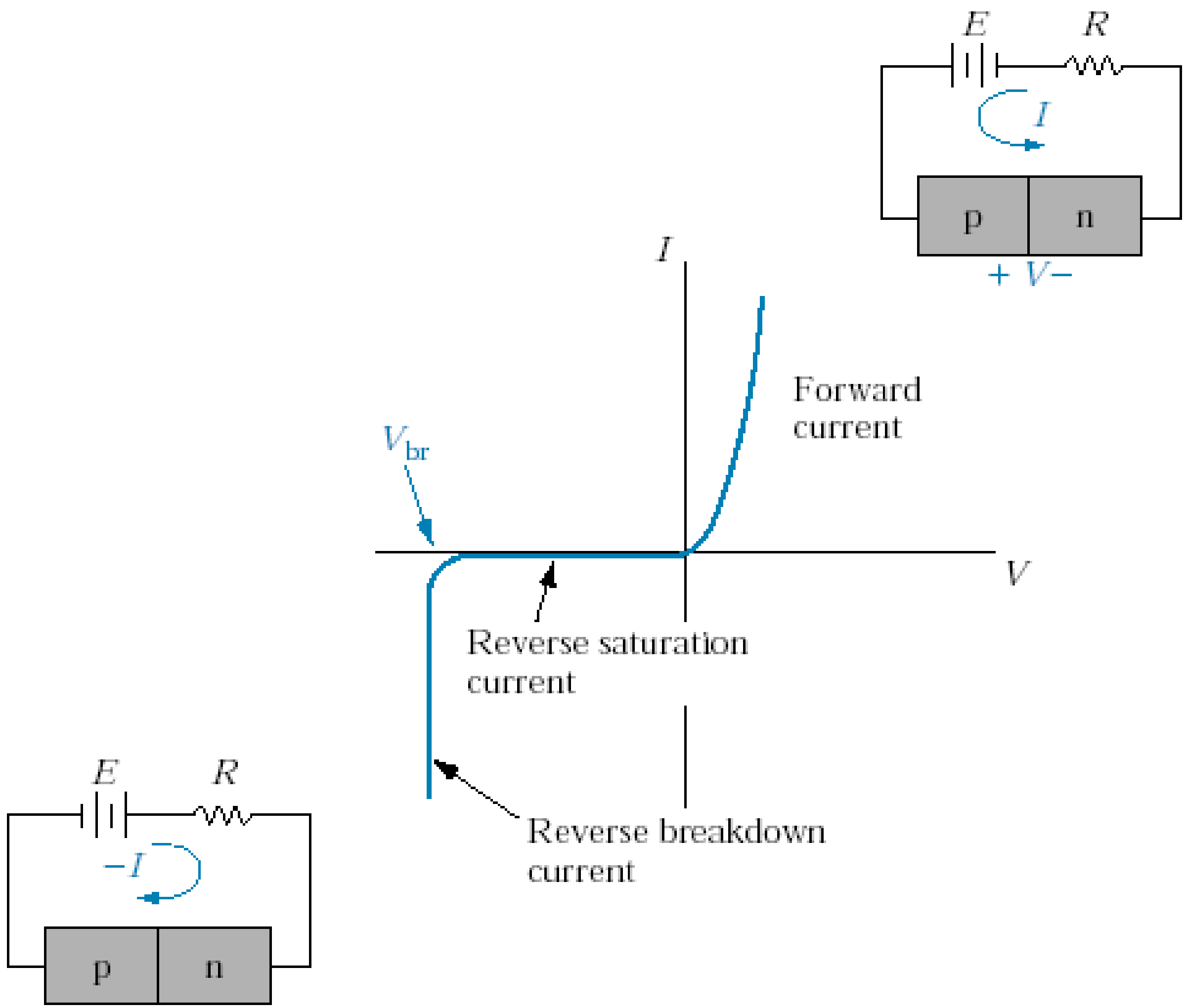
Reverse bias current

$$I = I_o = 4.37\times10^{-15}\,A$$

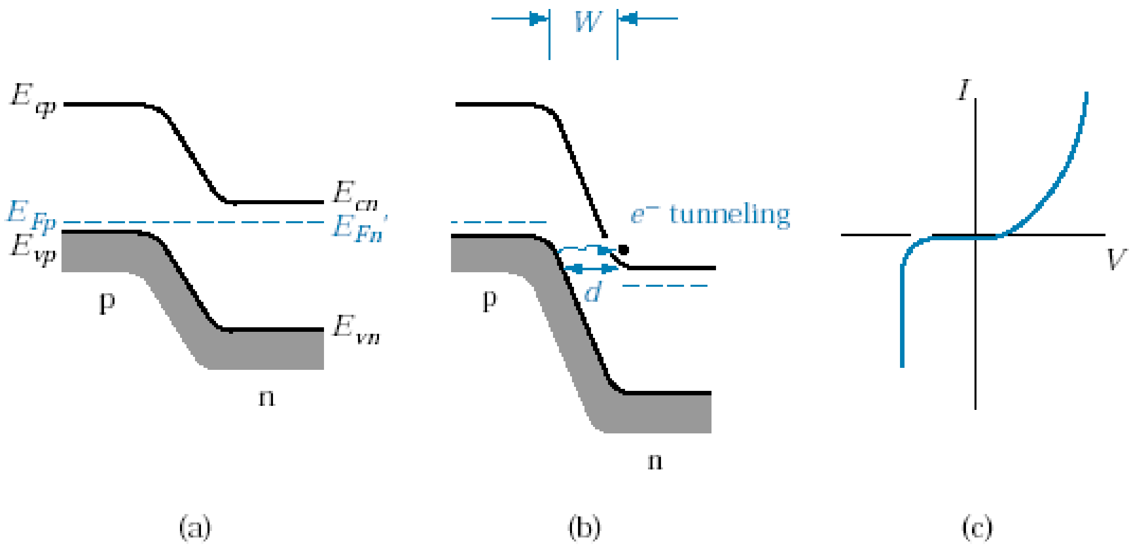
Diodes

- Reverse Breakdown
  - Zener
  - Avalanche
- Junction Capacitance
  - Switching Time
- Recombination and Generation
- Schottky Barriers

Reverse Breakdown



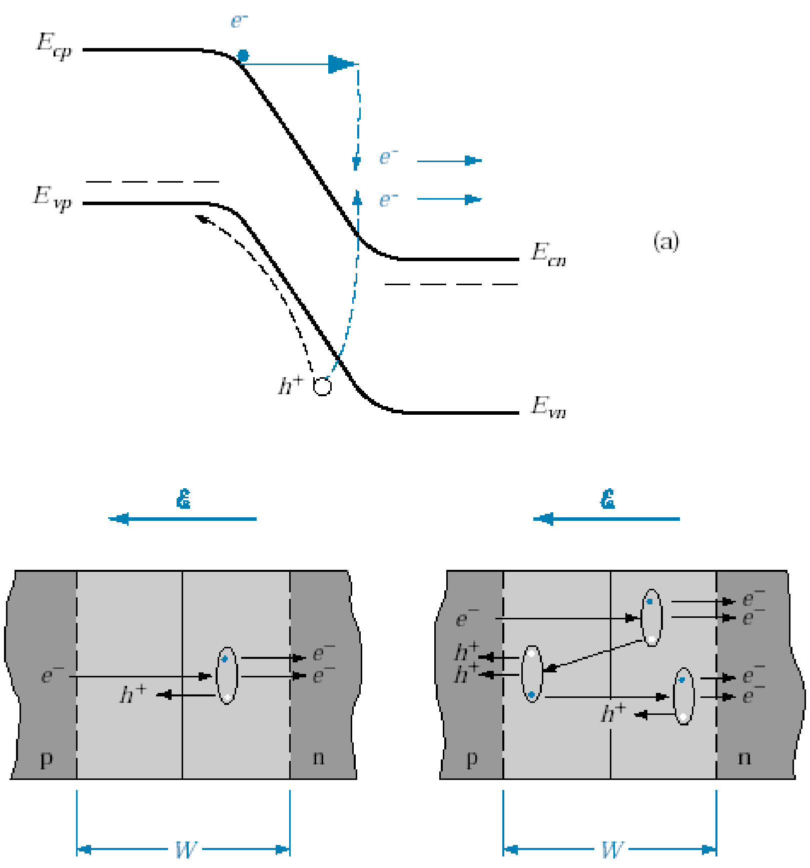
Zener Breakdown



Energy bands of heavily doped junctions can "cross" at relatively low reverse voltages, aligning high numbers of empty states with energetic carriers. The result is "tunneling".

Avalanche Breakdown

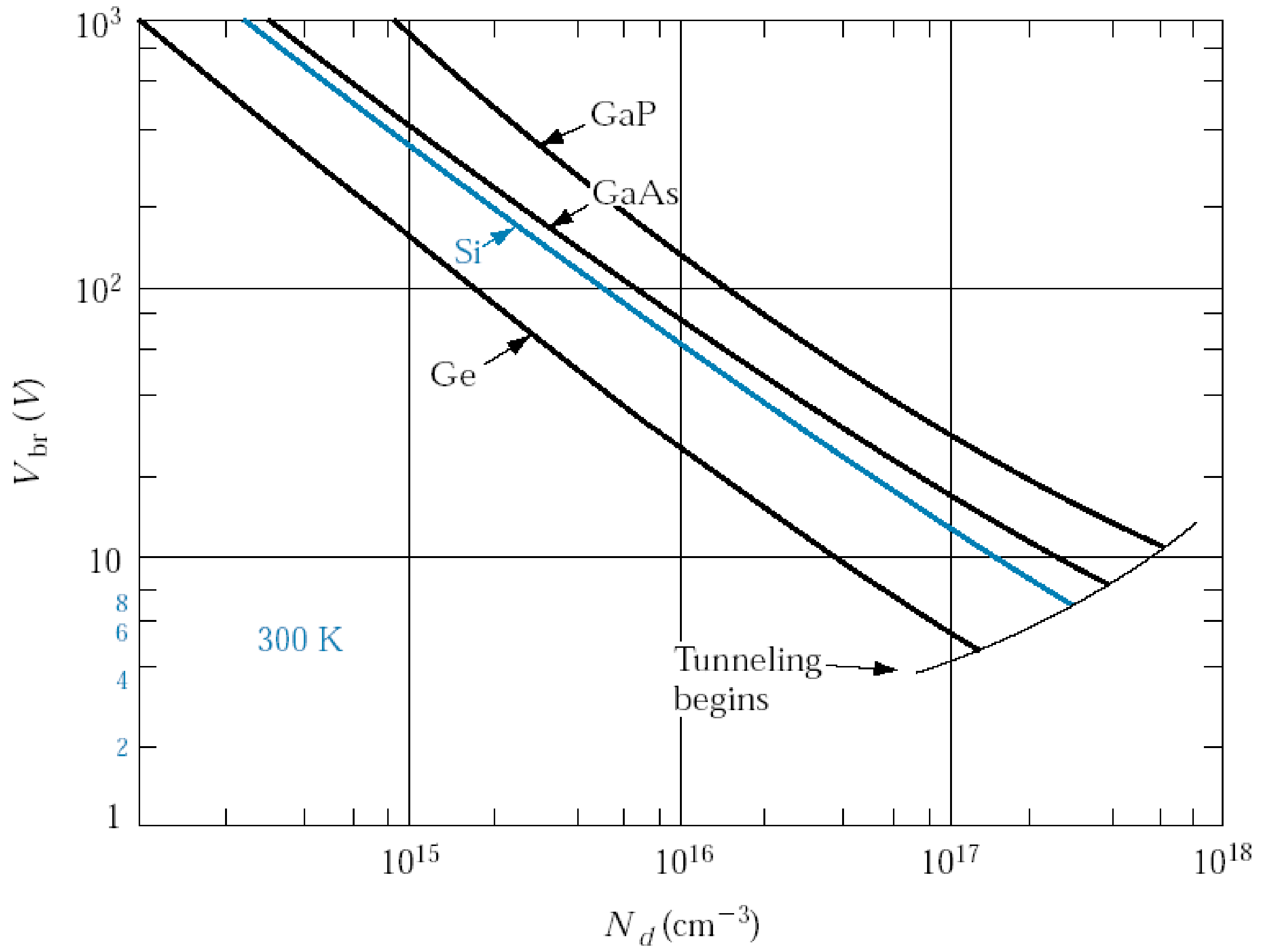
Tunneling is unlikely in lightly doped junctions. However, breakdown can occur due to "avalanche" creation of EHPs from collisions of the highly energized carriers transiting the depletion region.



(b)

(c)

Avalanche Breakdown vs. Doping in Various Semiconductors



Homework

Due in one week (June 15, 2015)

- 5.9 Fermi Energy Level
- 5.12 Forward bias current
- 5.19 Junction/transition region character
- 5.29 Breakdown and Punchthrough (bonus problem)

  Hint: *p+n* junction, so $x_{no}=W$

  Start w/energy and look at space charge (pp 167-169)

Junction Capacitance (charge storage)

AC conditions are important as primary use of the PN junction is as a switch. Stored charge always lags current

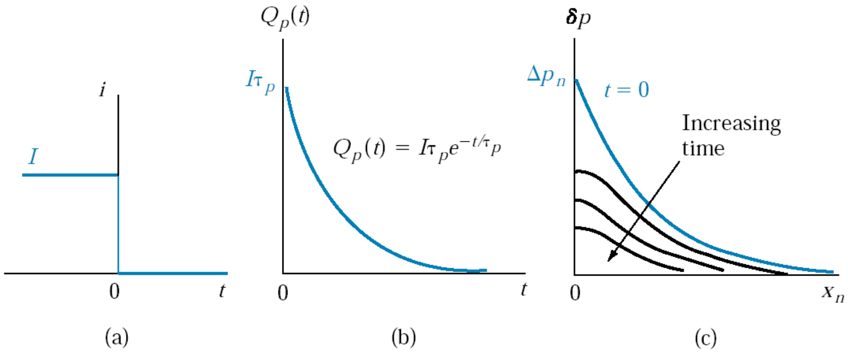
$$i(t) = \frac{Q_p(t)}{\tau_p} + \frac{dQ_p(t)}{dt}$$

Recombination Term

Injection Term (0 at steady state)

for a long n-region where hole current is injected at x=0 and is 0 at x=n

$$Q_p(t) = I\tau_p e^{-t/\tau_p}$$



This step function solution for charge leads to the quasi-steady state approximation for junction voltage

$$v(t) = \frac{kT}{q}\ln\left(\frac{I\tau_p}{qAL_p p_n}e^{-t/\tau_p} + 1\right)$$

Junction Capacitance (charge storage)

This step function solution for charge leads to the quasi-steady state approximation for junction voltage

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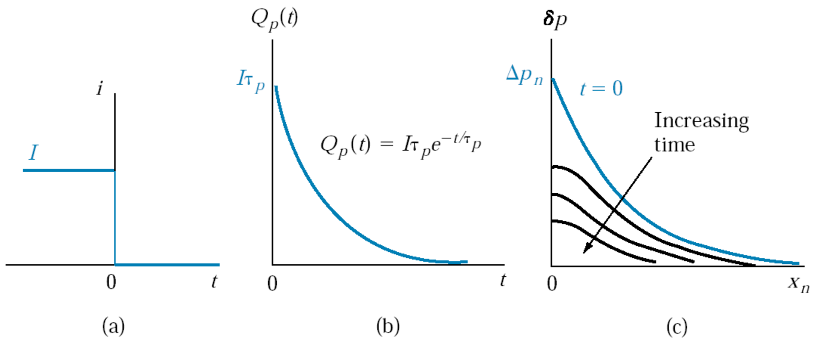


Though an approximation, *v(t)* is clearly is continuous (cannot change instantly) and thus will limit switching speed.

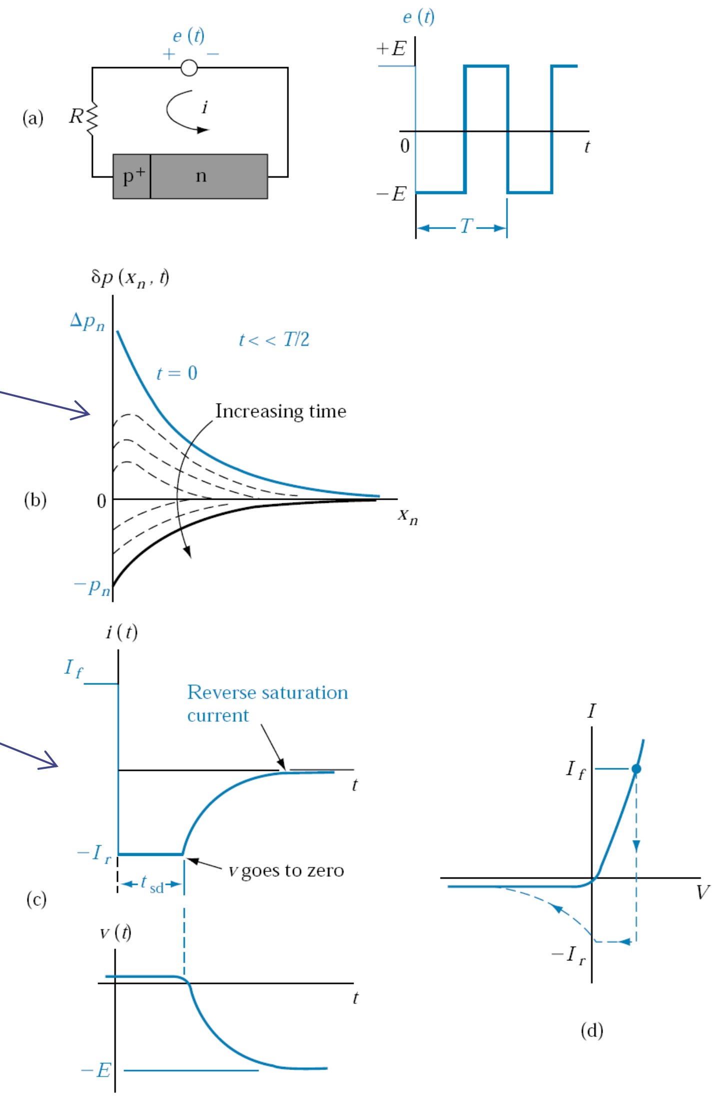
The junction stores charge and thus has capacitance.

Switching

At $t=0^+$ the stored charge will become a negative current much greater than I_0, and will cause a reverse voltage across the junction.

The reverse current continues for a finite time, after which it relaxes exponentially to I_0.

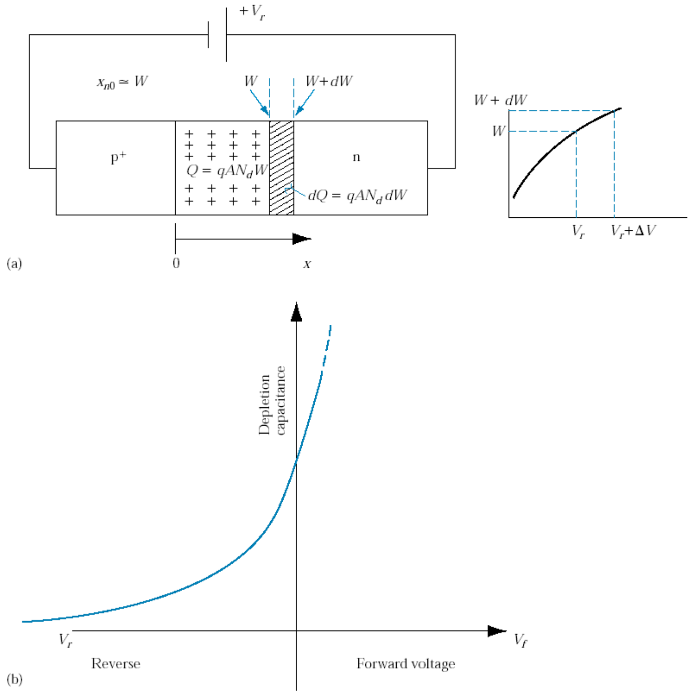
Narrow regions can therefore switch faster (less capacitance) but are harder to make and more sensitive to ξ-field…oh well…



Stitching Diodes

- Should have minimal R_f to reduce power losses and to result in lower I_R.
- Geometric and material design can address R_f.
- Another approach is to shorten τ by doping with gold.
- ~10^{15} Au atoms/cm^3 will reduce τ and t_{sd} by an order of magnitude.

Depletion or Junction Capacitance – Reverse Bias



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

V_o dependant, Varactor

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

W correspond to plate separation, just like a normal capacitor

$$C_j = \frac{A}{2}\left[\frac{2q\varepsilon}{(V_0 - V)}N_d\right]^{\frac{1}{2}}$$

Simplified for p^+n junctions

Capacitance can be used to estimate doping!

Example 5-6

Calculate the depletion capacitance of the diode in example 5-4.

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

$$= \sqrt{8.85\times10^{-14}\times11.8}\left(10^{-4}\right)\left[\frac{1.6\times10^{-19}}{2(0.695+4)}\frac{10^{15}10^{17}}{10^{15}+10^{17}}\right]^{\frac{1}{2}}$$

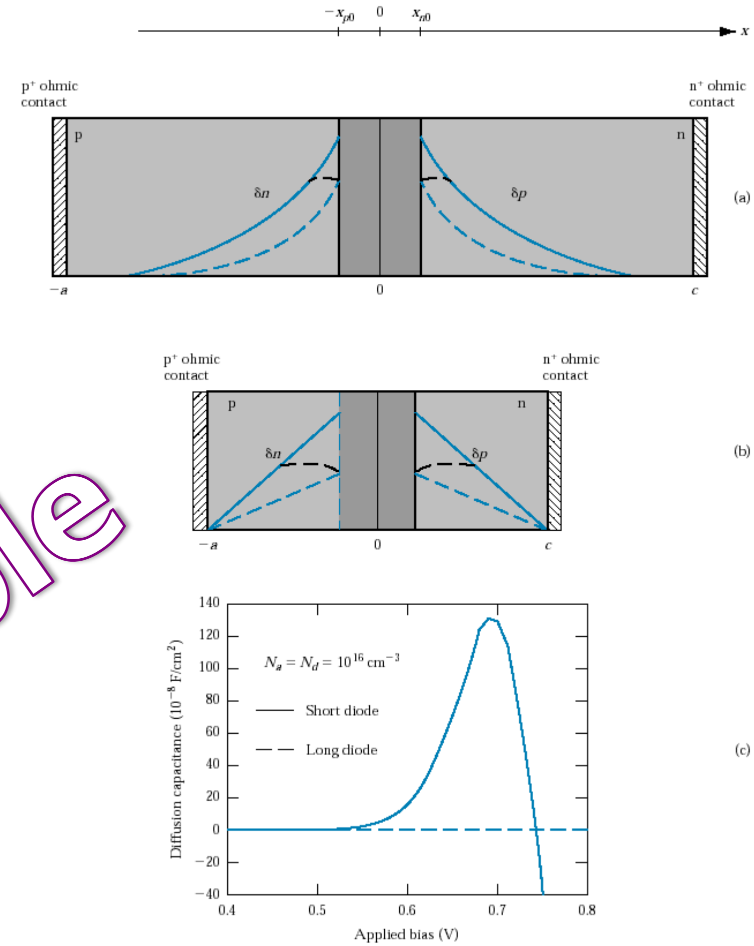
$$= 4.198\times10^{-13}F$$

Diffusion Capacitance Forward Bias

C_s because it relates to stored charge

Often negligible but can be an issue with short base devices.

Not Testable



Junction Profiles

Abrupt junction capacitance varies with the square root of V_r

But in linearly graded junctions the variation is proportional to V_r^{-n}

n>1/2 Hyperabrupt junctions make great variable reactors (variactors)

Three doping profiles are defined by G^m where $n=1/m+2$

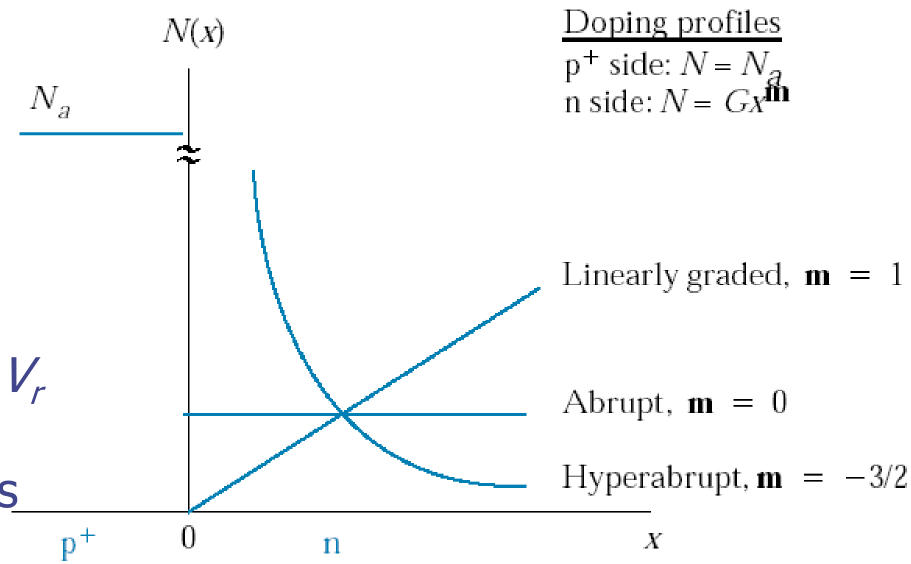


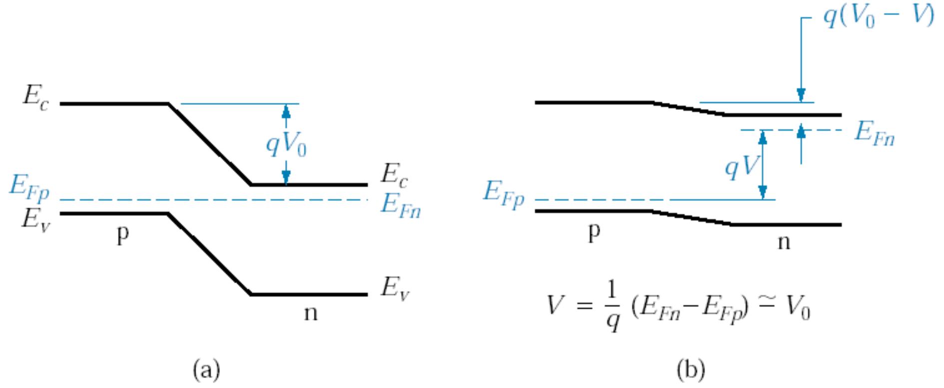
Figure 5–31
Graded junction profiles: linearly graded, abrupt, hyperabrupt.

Not Testable

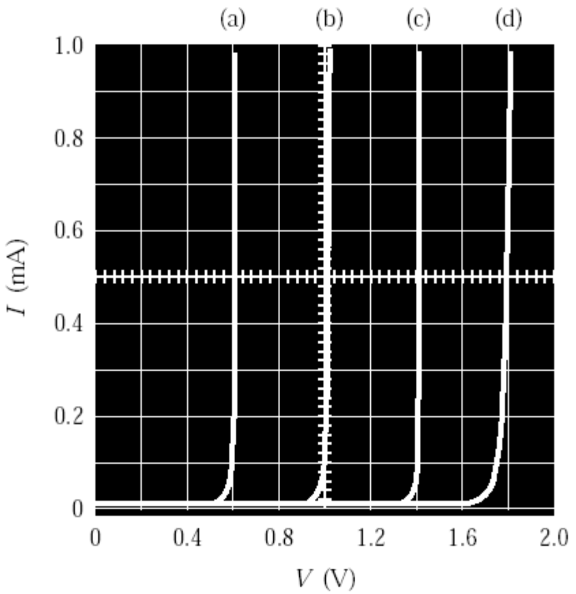
Deviations from the Simple Model

- Effects of contact potential which cause the IV characteristics to vary with forward bias
- Effects of majority carrier concentration changes causing IV variation due to changes in carrier injection
- Recombination and generation within the transition region, which differ between long and short base devices
- Ohmic effects
- Graded junctions (theory derived from abrupt junction analysis)

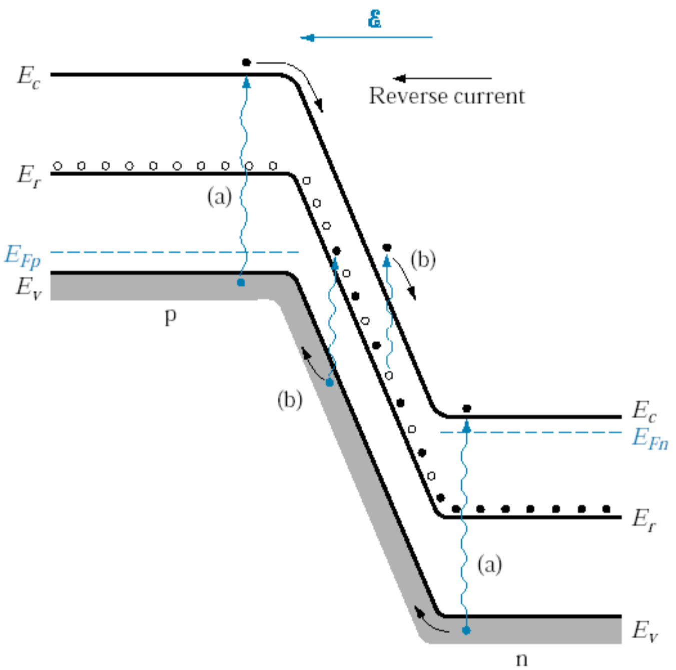
Carrier Injection vs Contact Potential



$$I \propto e^{\frac{qV}{2kT}}$$



Recombination Generation

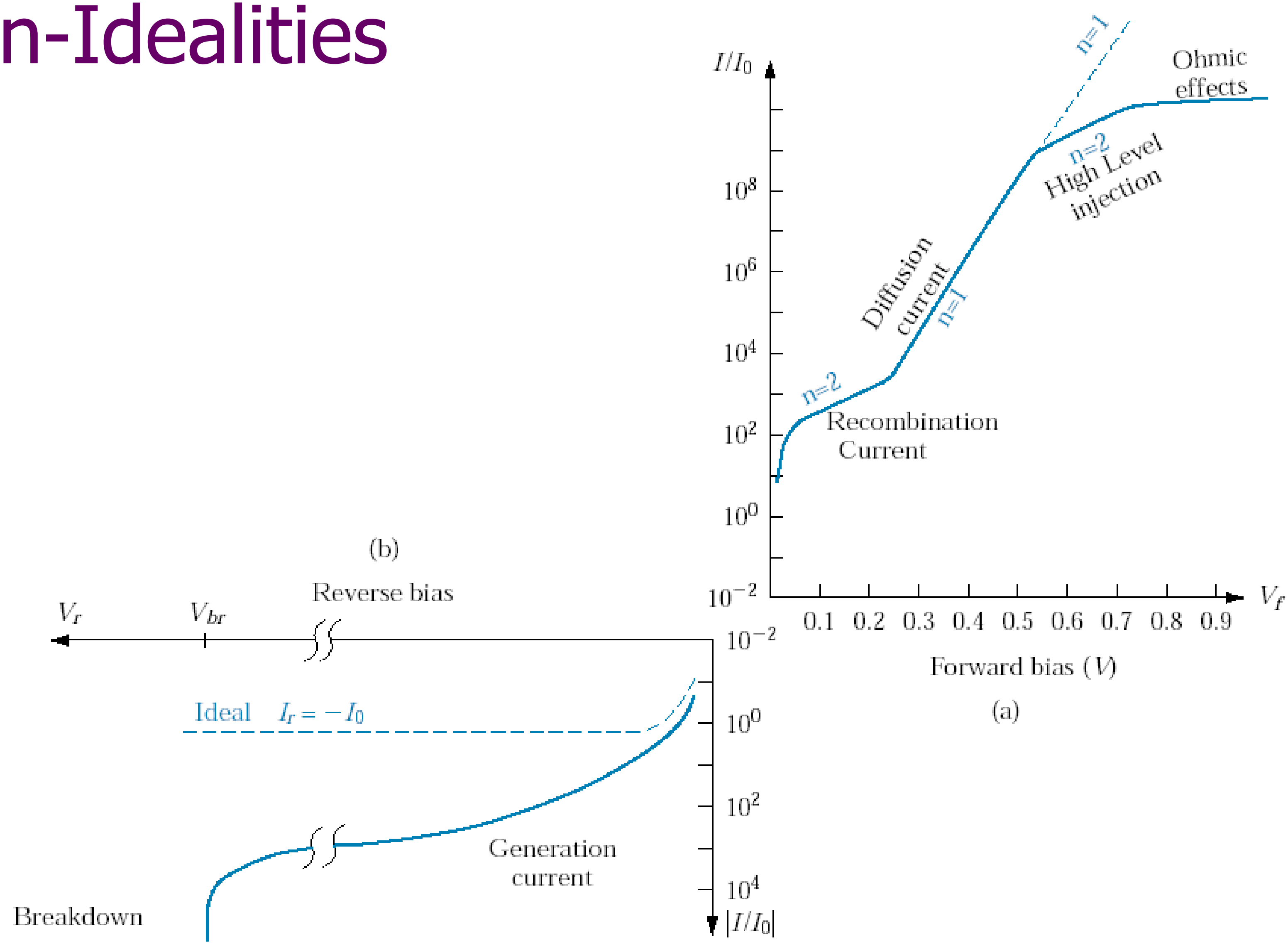


W is thought of as 'depleted' but in fact has recombination and generation going on all the time.

We handle this with the ideality factor '*n*', which varies between 1 and 2.

$$I = I_o'\left(e^{qV/nkT} - 1\right)$$

Effects of Non-Idealities



Graded Junctions

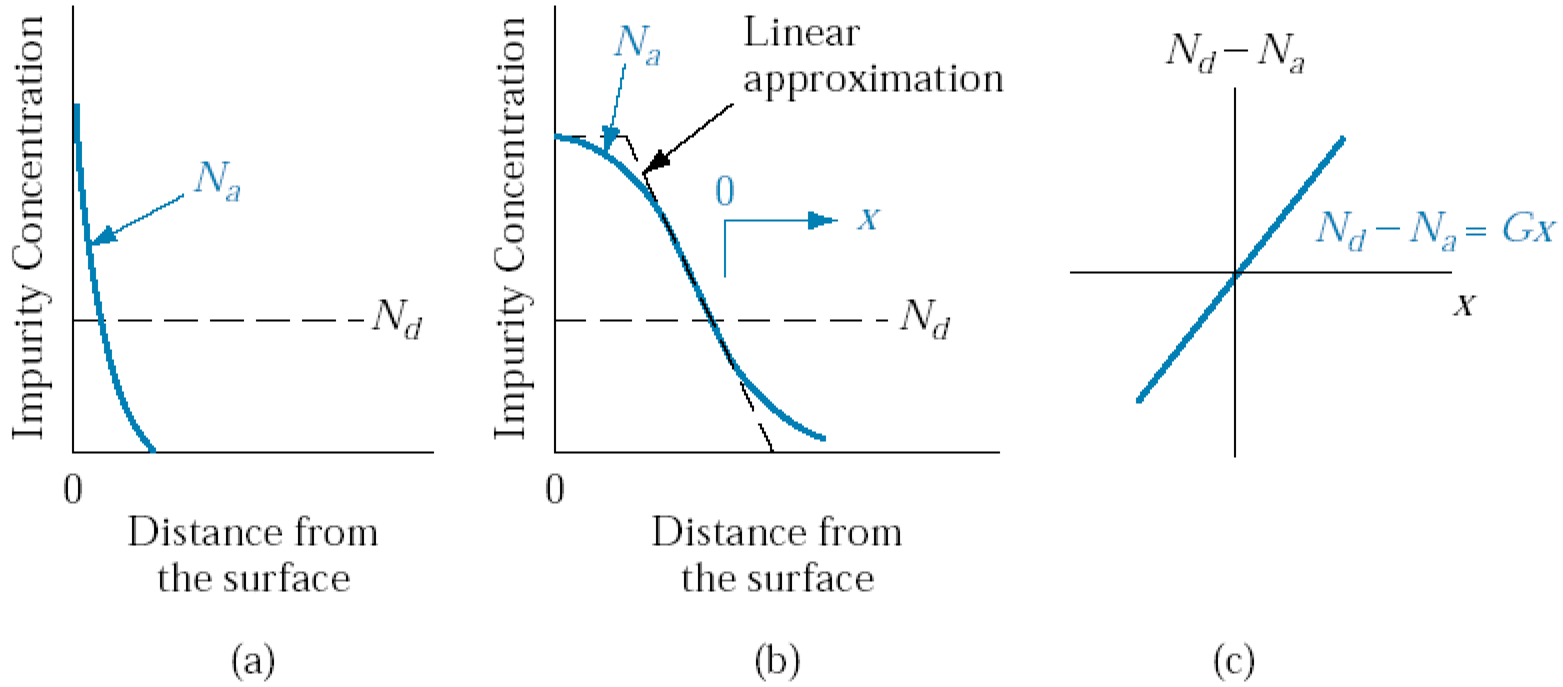
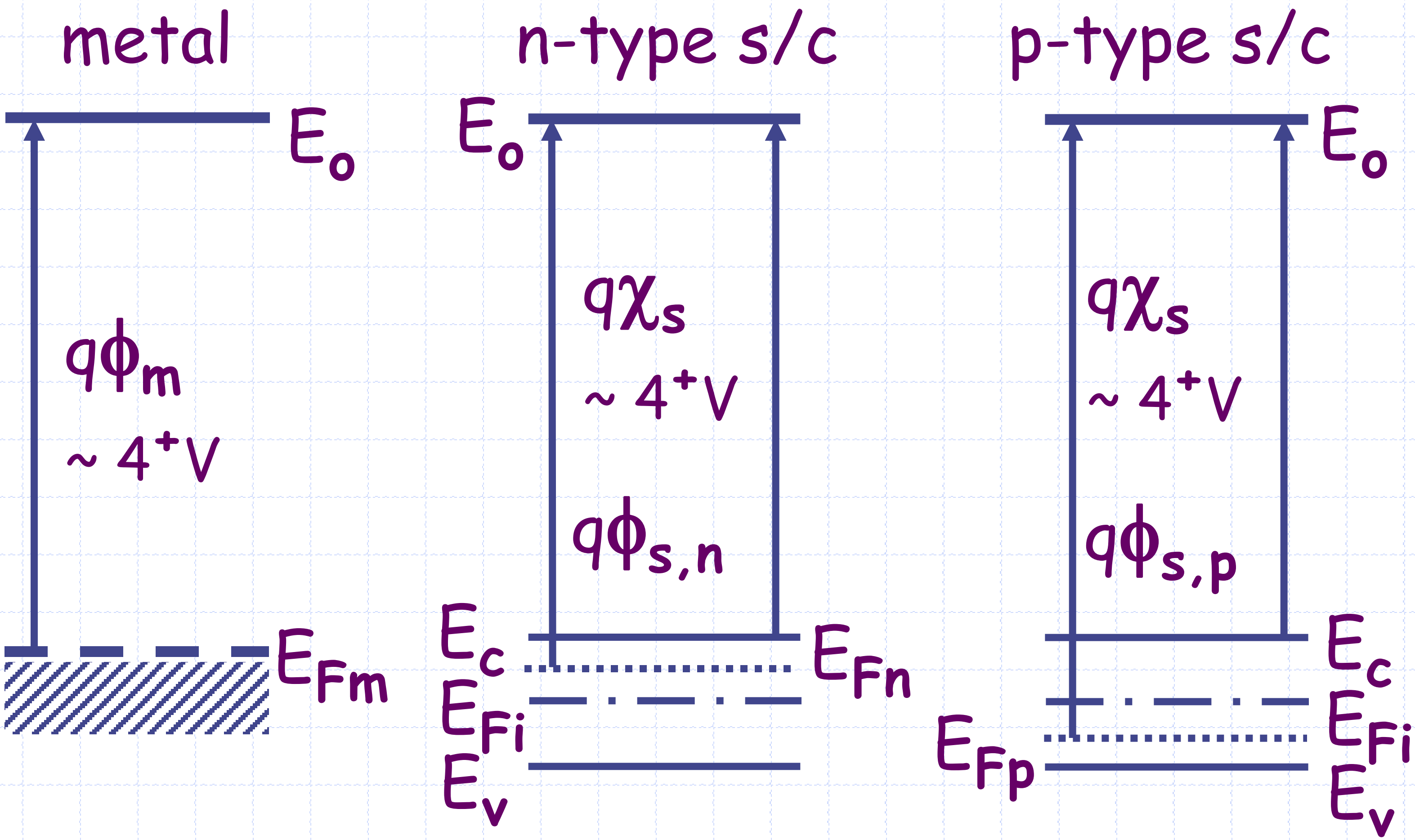


Figure 5–38
Approximations to diffused junctions: (a) shallow diffusion (abrupt); (b) deep drive-in diffusion with source removed (graded); (c) linear approximation to the graded junction.

Schottky Barrier Diodes

A simple metal to semiconductor contact

Metal, n- and p-Type Band Models

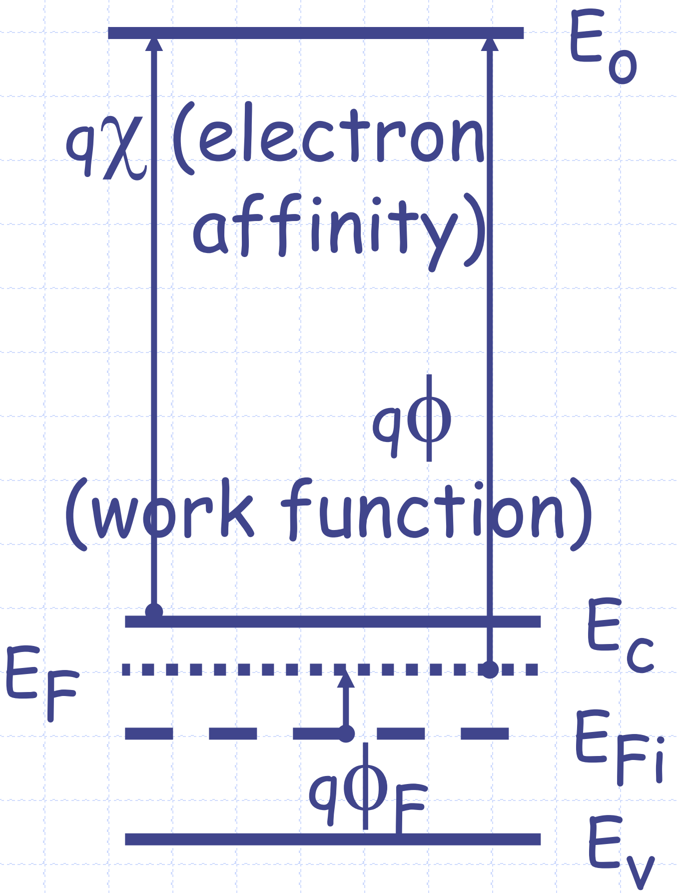


Metal/Semiconductor Contacts

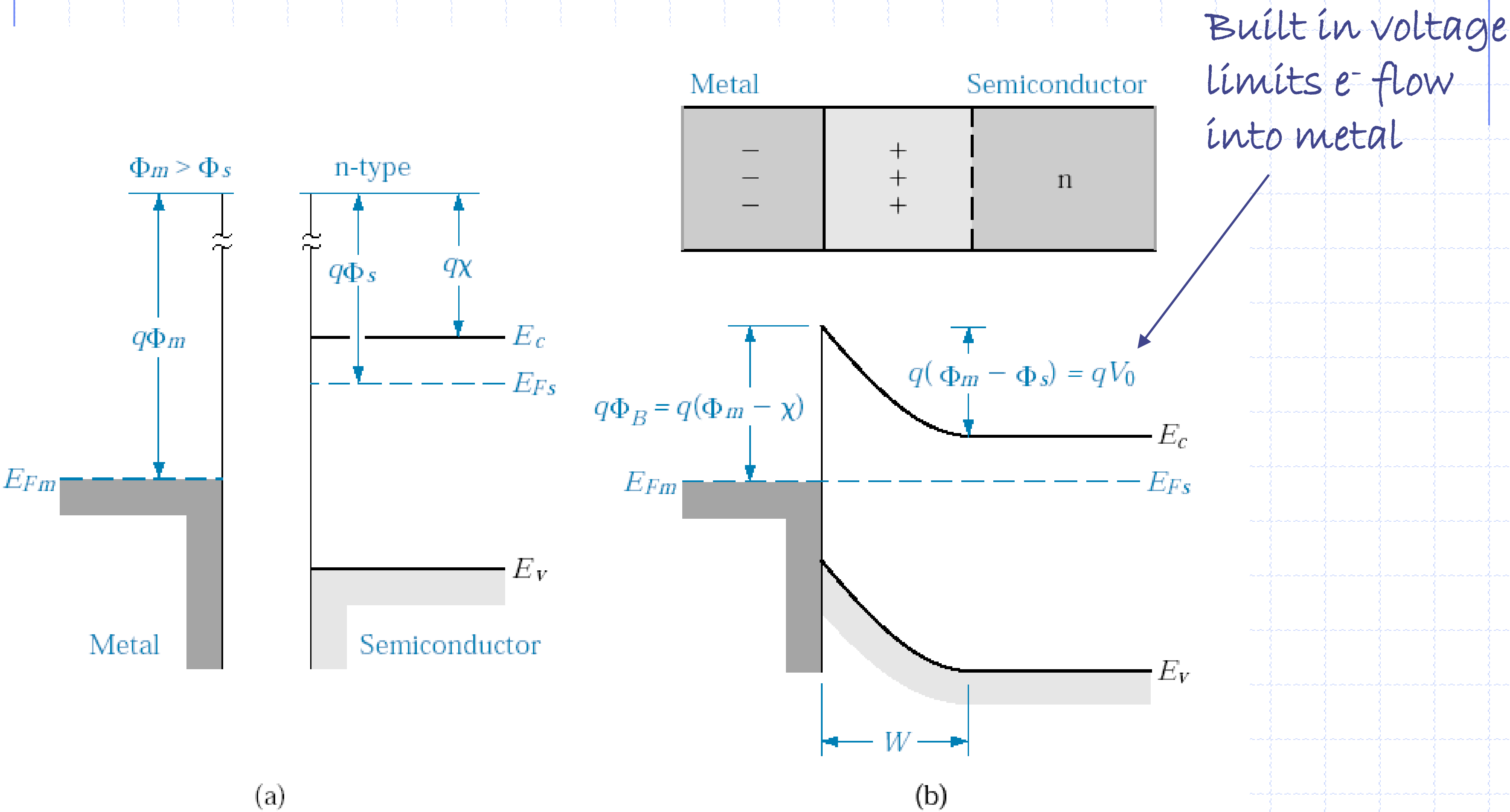
- E_F equilizes across the junction and system.
- E_o(the free level) is continuous across the junction.

Note: $q\chi = 4.05\ eV$ (Si),

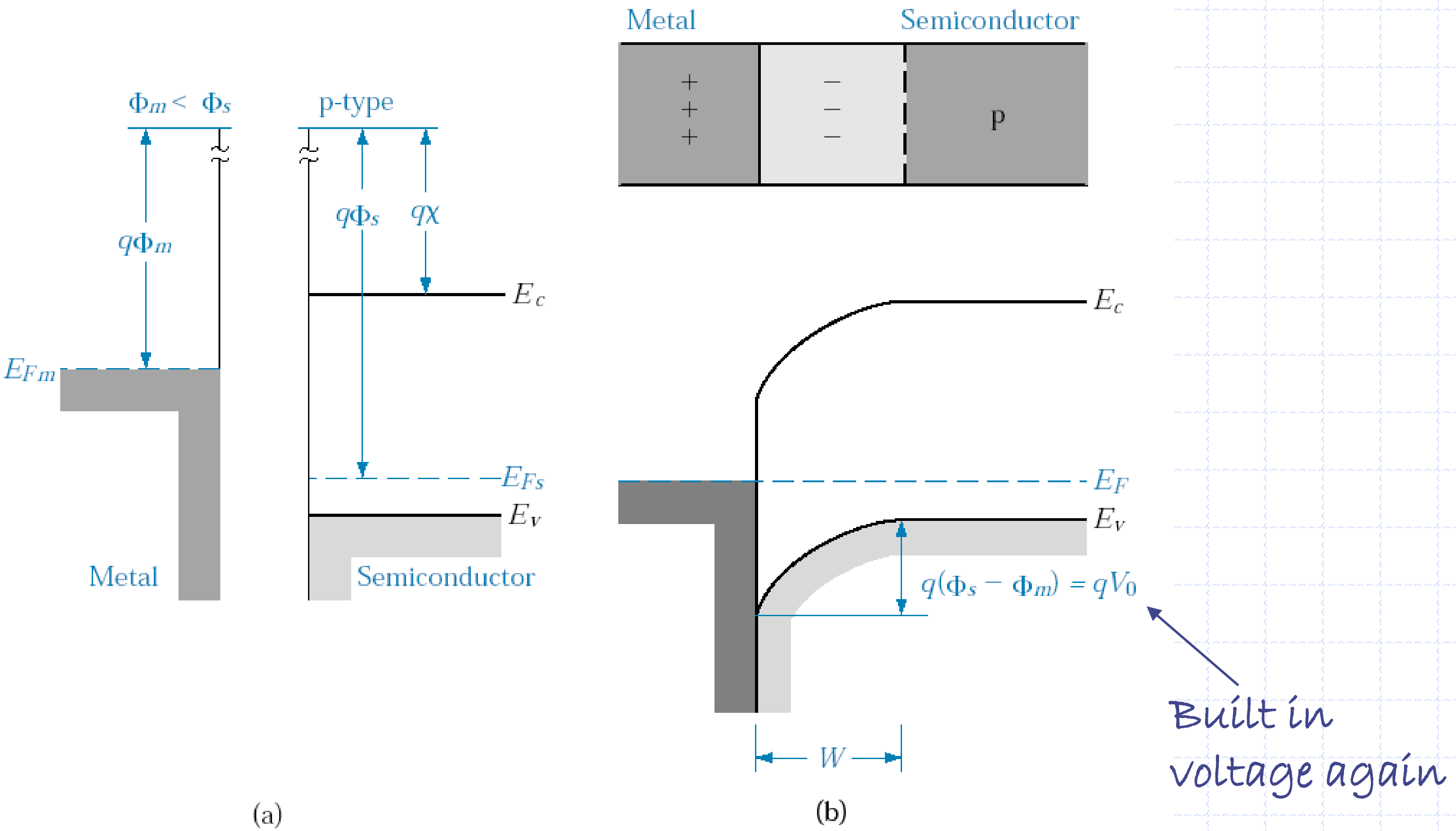
and $q\phi = q\chi + E_c - E_F$



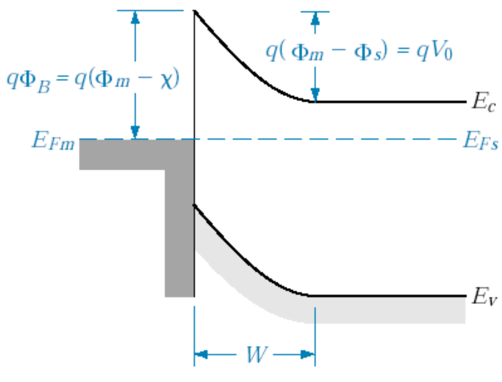
Schottky Barrier
($\Phi_m > \Phi_s$, n-type semiconductor)



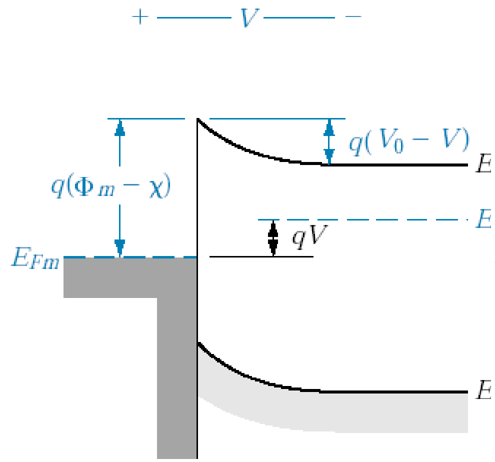
Schottky Barrier
($\Phi_m < \Phi_s$, p-type semiconductor)



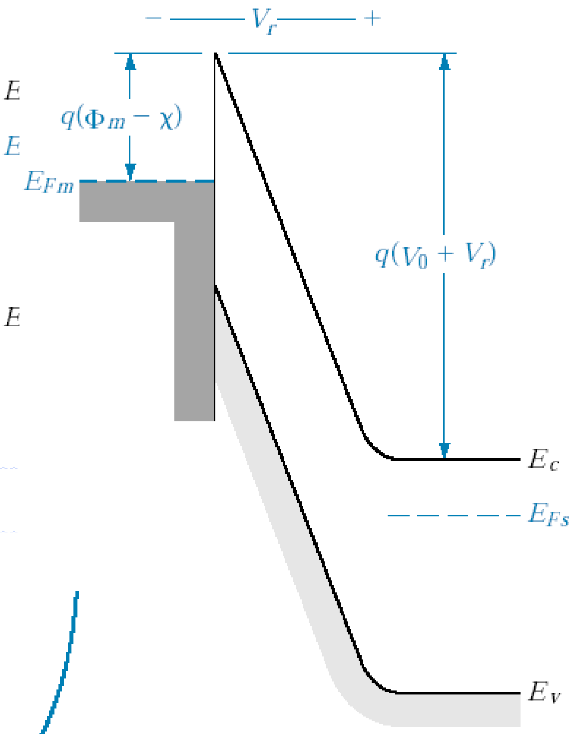
Schottky Barrier Characteristic (n-type)



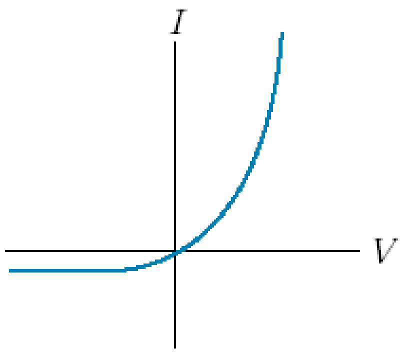
No bias



Forward Bias

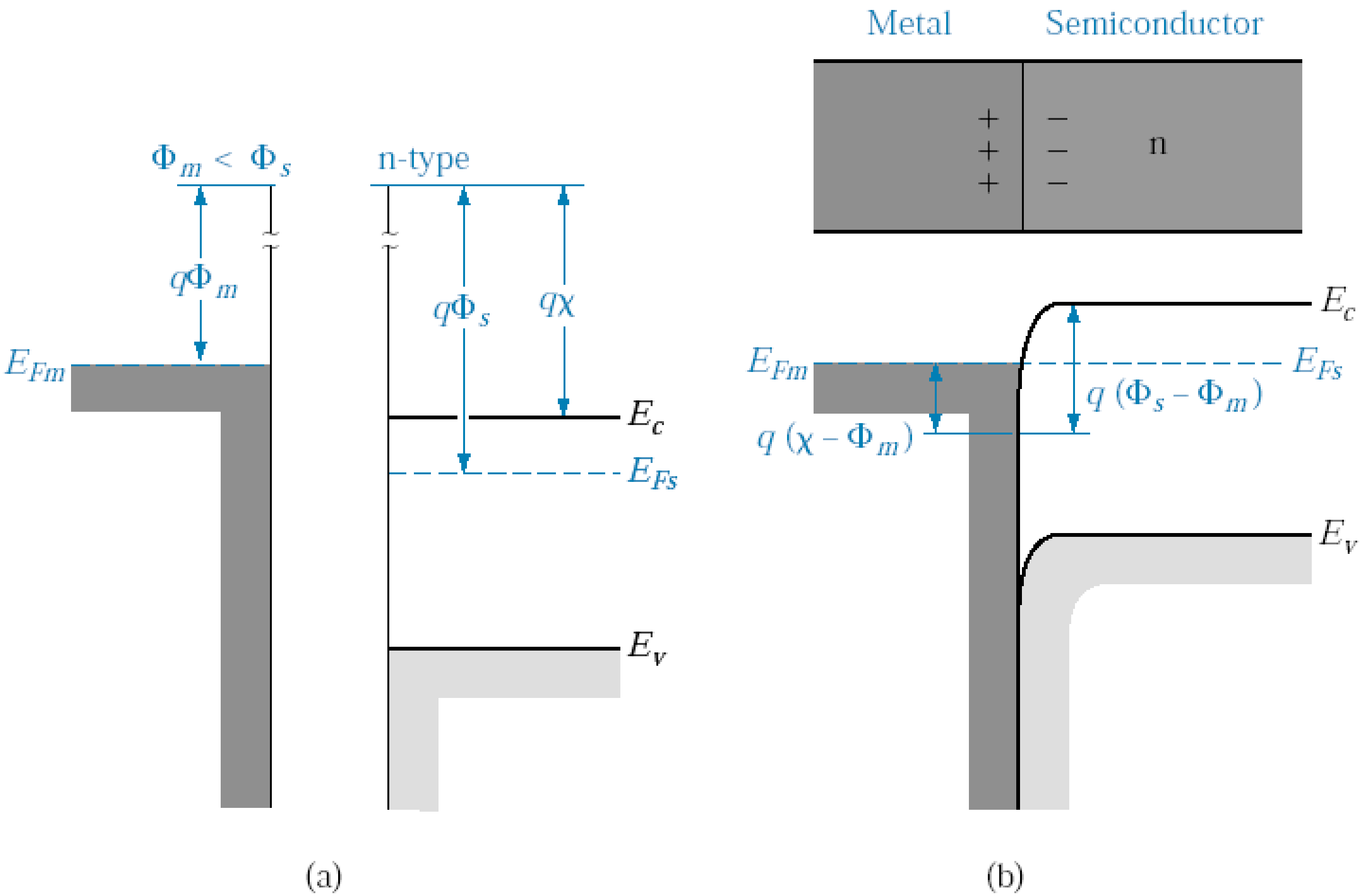


Reverse Bias

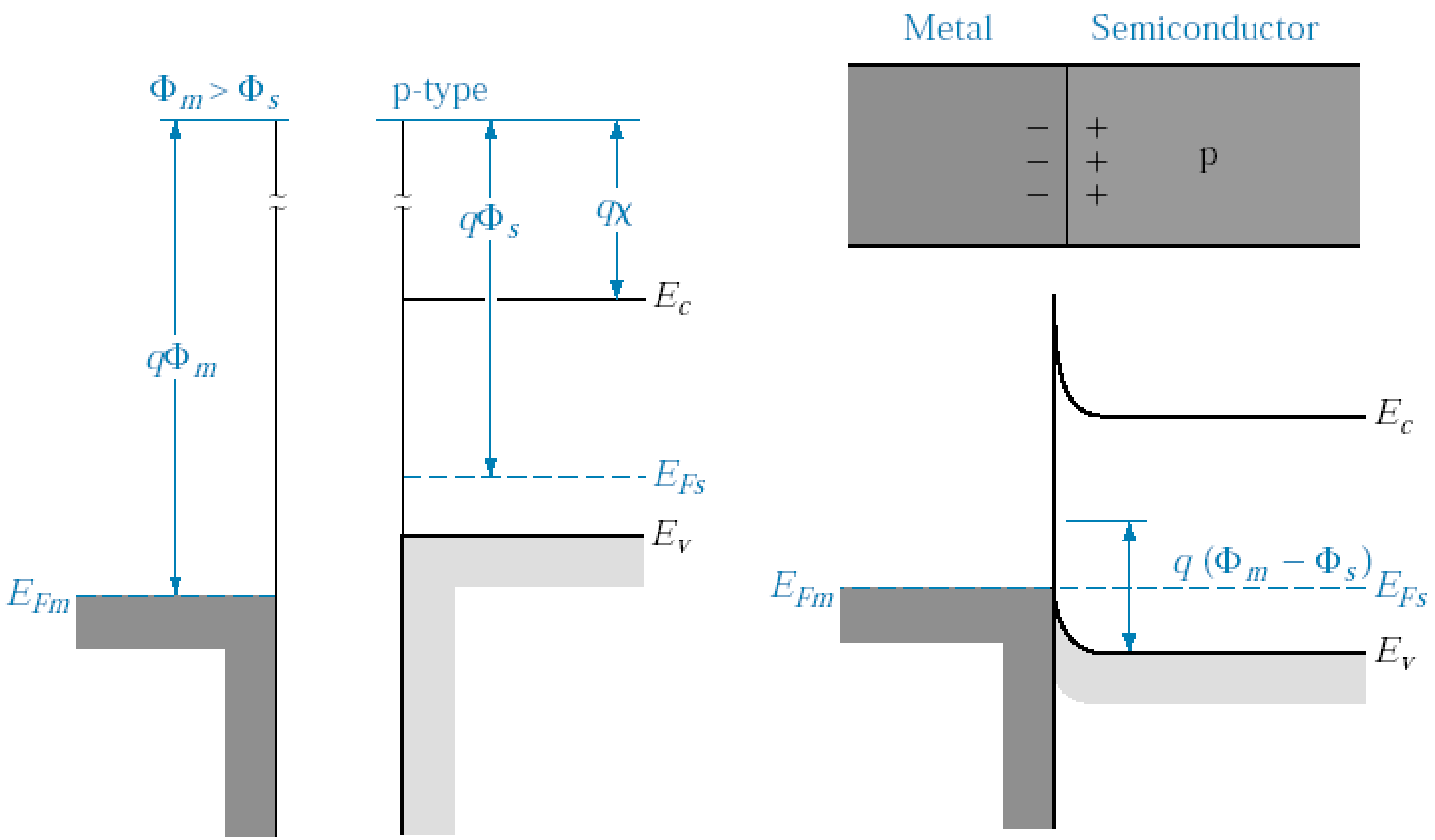


I-V Characteristic

Ohmic Contact
(n-type, $\Phi_m < \Phi_s$)



Ohmic Contact (p-type, $\Phi_m > \Phi_s$)



Schottky Summary

p-Type	$\Phi_m > \Phi_s$	Ohmic
p-Type	$\Phi_m < \Phi_s$	Schottky Barrier
n-Type	$\Phi_m > \Phi_s$	Schottky Barrier
n-Type	$\Phi_m < \Phi_s$	Ohmic