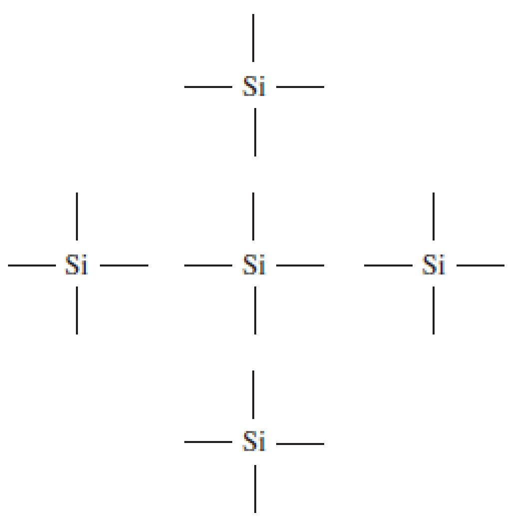
Semiconductor Materials

Table 1.2 A portion of the periodic table

III	IV	V
5 **B** Boron	6 **C** Carbon	
13 **Al** Aluminum	14 **Si** Silicon	15 **P** Phosphorus
31 **Ga** Gallium	32 **Ge** Germanium	33 **As** Arsenic
49 **In** Indium		51 **Sb** Antimony

↓	↓	↓
3 valance electrons	4 valance electrons	5 valance electrons

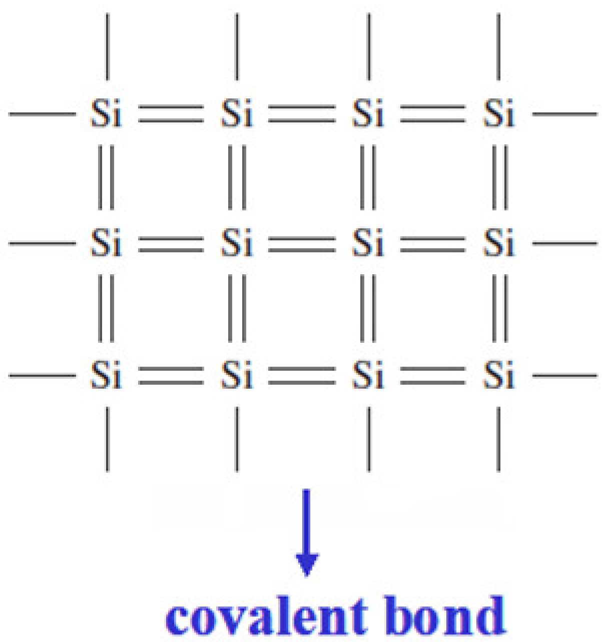
Each silicon atom has four valance electrons.



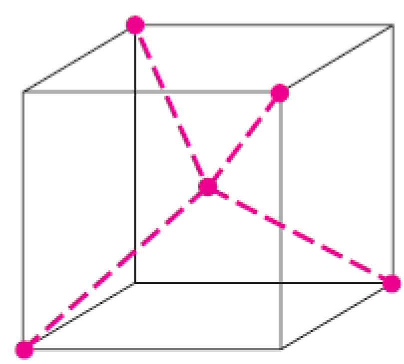
Intrinsic Semiconductor

(single crystal semiconductor material with no impurity atoms)

When silicon atoms come into close proximity, the valance electrons interact.



Crystal structure:



Two electrons are shared between two neighbor atoms.

3D tetrahedral configuration

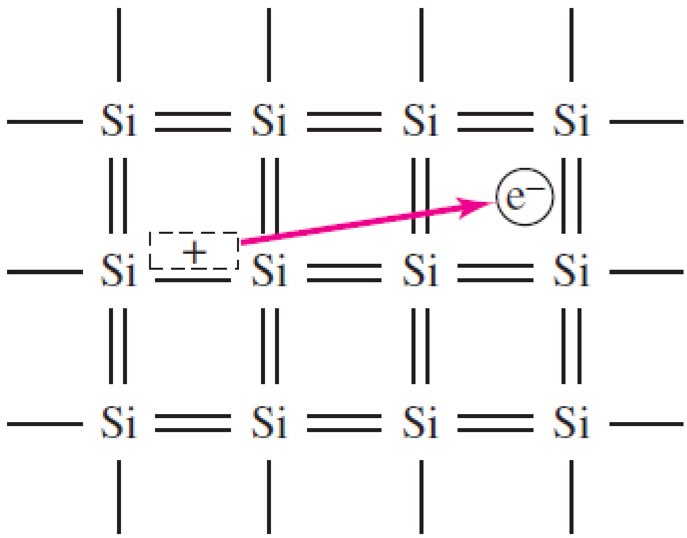
At T=0 K, each electron is in its lowest possible energy state. Covalent bond positions are filled. If a small electric field is applied to this material, valance electrons will not be able to move.

⇒ no charge flow, behave as an insulator.

Intrinsic Semiconductor (T > 0 K)

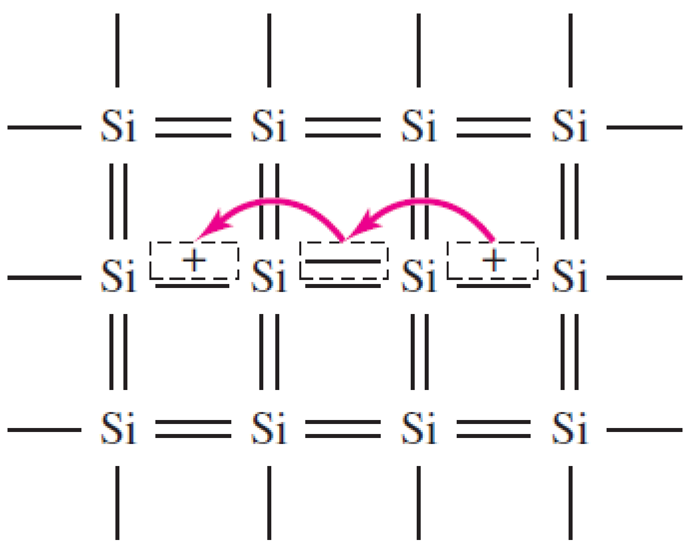
- Some valance electrons may gain enough thermal energy to break the covalent bond and move away

$\Rightarrow$ becoming free electrons (in the conduction band)



- A valance electron hopping over neighbor empty states

$\Rightarrow$ a positively charged “particle” is moving: hole



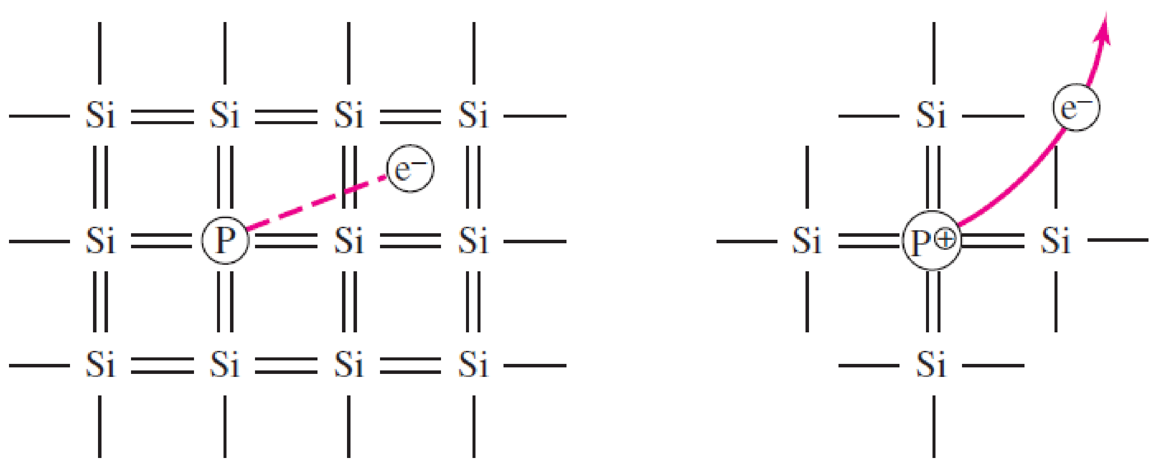
Mobile electrons and holes are generated in equal amount.
Two types of charged particles contribute to current:

Extrinsic Semiconductor
(Doped semiconductors)

— semiconductor materials containing impurity atoms.

n-type semiconductor

Silicon doped with phosphorus atom (group V)



The fifth valance electron is more loosely bound to the phosphorus atom (by the coulomb force) and at room temperature gains sufficient thermal energy to very easily break the bond.

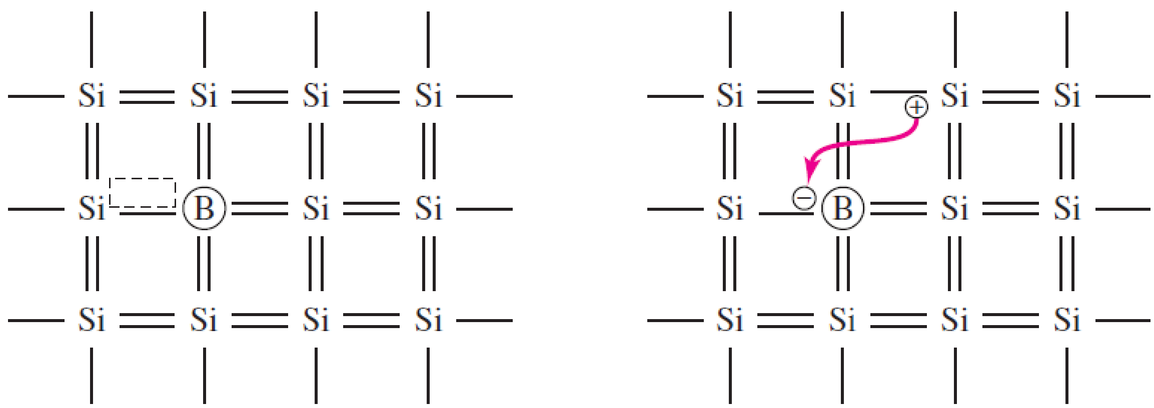
$\Rightarrow$ becoming free electron.

The phosphorus atom
— a donor impurity (donates an electron that is free to move).

- free electrons are created without generating holes;
- "positive" phosphorus atoms cannot move and do not contribute to current.

p-type semiconductor

Silicon doped with boron atom (group III)



Three valance electrons of boron contribute to three covalent bonds; one covalent bond position is open. At room temperature adjacent silicon valance electron has sufficient thermal energy to move into this position.

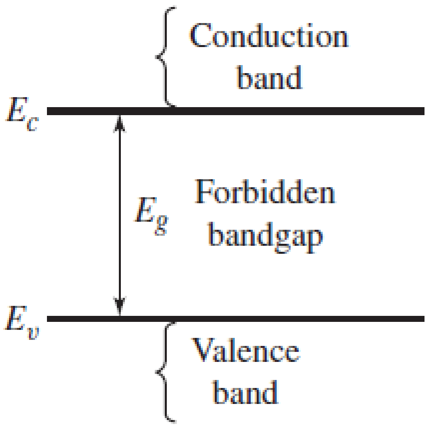
⇒ creating a mobile hole.

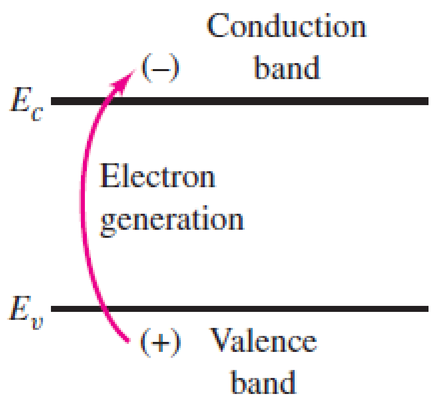
The boron atom

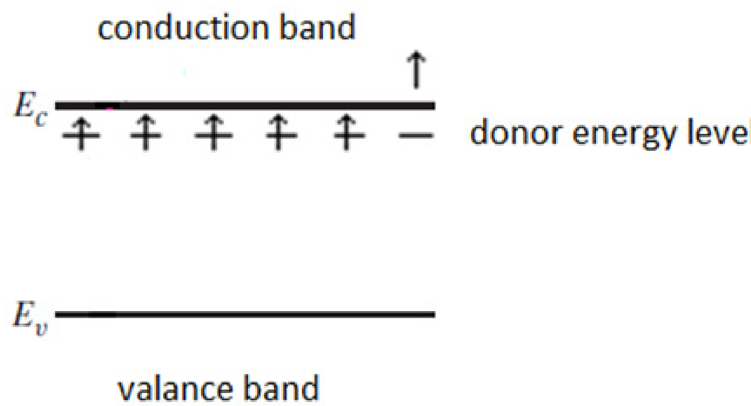
— an acceptor impurity (accepts a valence electron).

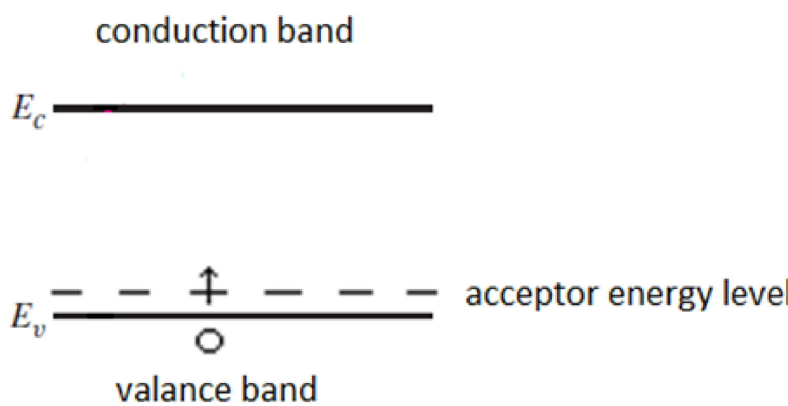
- creation of mobile holes without free electrons being generated;
- "negative" boron atoms cannot move and do not contribute to current.

Energy Band Diagrams of Semiconductors









Bandgap energy E_g:	very large 3~6 eV	insulator
	small ~ 1 eV	semiconductor
	conduction band is half-filled	conductor

Densities of Electrons and Holes in Thermal Equilibrium
(carriers are generated by thermal excitation.)

Intrinsic Semiconductor:

Electrons and holes are generated in equal amount.

$$n_i = BT^{3/2}\, e^{-\frac{E_g}{2k_B T}}$$

T – temperature
k_B – Boltzmann's constant
E_g – bandgap energy
B – constant related to the specific semiconductor material

Table 1.2 Semiconductor constants

Material	E_g (eV)	B ($cm^{-3} K^{-3/2}$)
Silicon (Si)	1.1	5.23×10^{15}
Gallium arsenide (GaAs)	1.4	2.10×10^{14}
Germanium (Ge)	0.66	1.66×10^{15}

Excess Carriers

— Carriers generated by mechanisms other than thermal excitation.

When a voltage is applied to, or a current exists in a semiconductor device, the semiconductor is really not in equilibrium.

For example, when high energy photons are incident on a semiconductor, electrons can be lifted from the valence band to the conduction band, producing electron-hole pairs.

These additional electrons and holes are called excess electrons and excess holes.

Electron-hole recombination

A free electron may recombine with a hole.

→ reducing the excess electrons and excess holes.

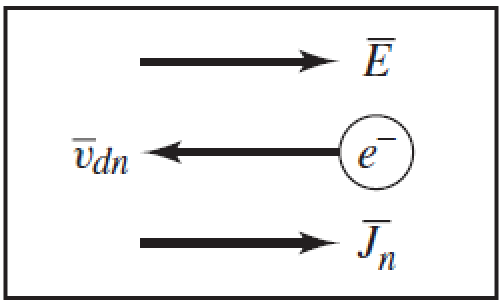
The mean time over which an excess electron and hole pair exist before recombination is called the excess carrier lifetime. In the steady state, electron-hole generation is balanced by the electron-hole recombination.

Currents in Semiconductor

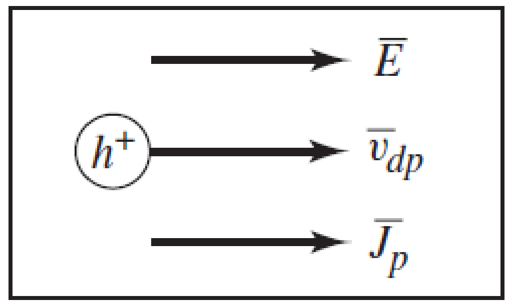
Drift Current

— movement of charges caused by an applied electric field.

drift of electron

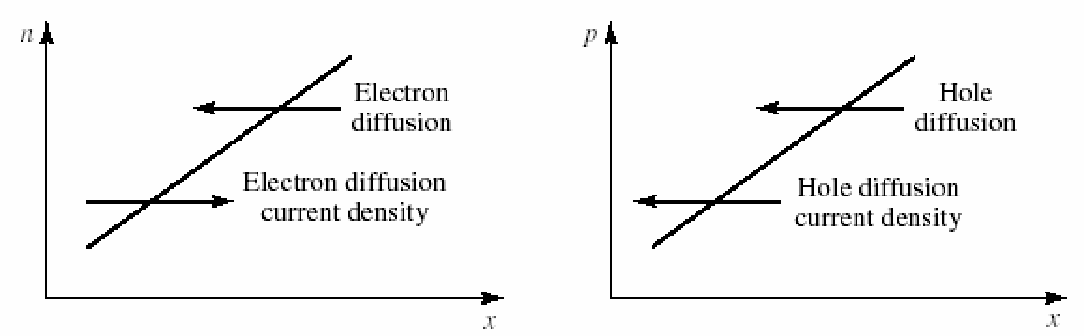


drift of hole



Diffusion Current

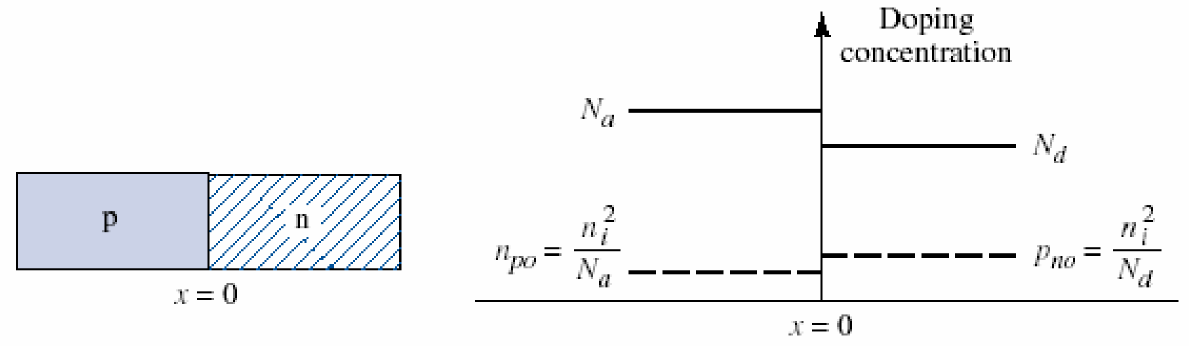
With diffusion, particles flow from region of higher concentration to region of lower concentration.



Statistically, electrons (holes) move at an average speed determined by the temperature, in random directions and with equal probability in any direction. There are more particles in higher concentration region than in lower concentration region.

$\Rightarrow$ Net flow of particles moving from the high concentration region toward the low concentration region.

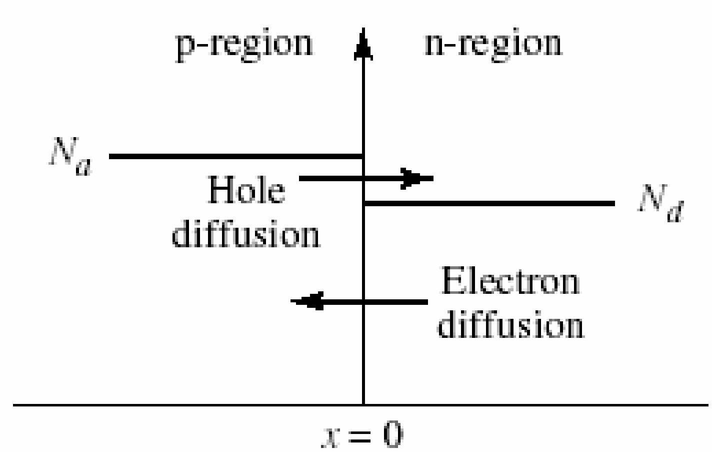
The pn Junction



Metallurgical junction: large density gradient in both electron and hole concentration occurs across this junction.

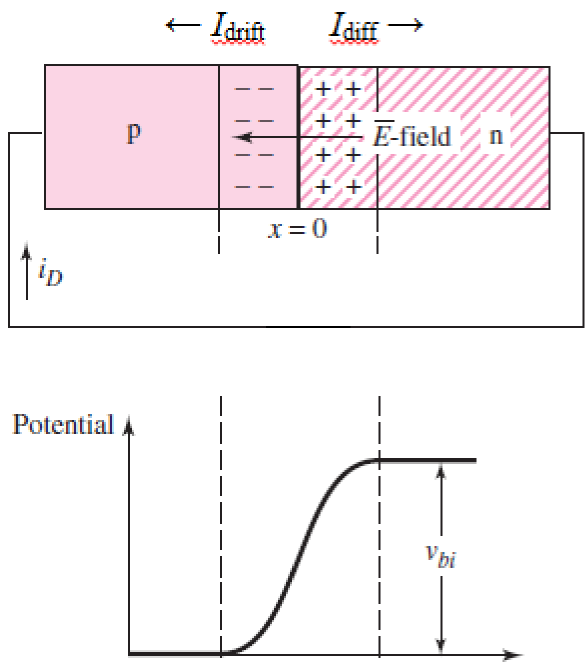
Diffusion of electrons from *n*-region into *p*-region.

Diffusion of holes from *p*-region into *n*-region.



pn-Junction in Equilibrium (zero bias)

These diffusions of majority carriers uncover negatively charged acceptor ions in the p-region and the positively charged donor ions in the n-region.



- Diffusion of majority electrons and holes creates a space-charge region.

  (also called depletion region, no mobile electrons and holes, 0.1–1 μm)
- Set up an internal electric field (built-in potential barrier V_{bi})

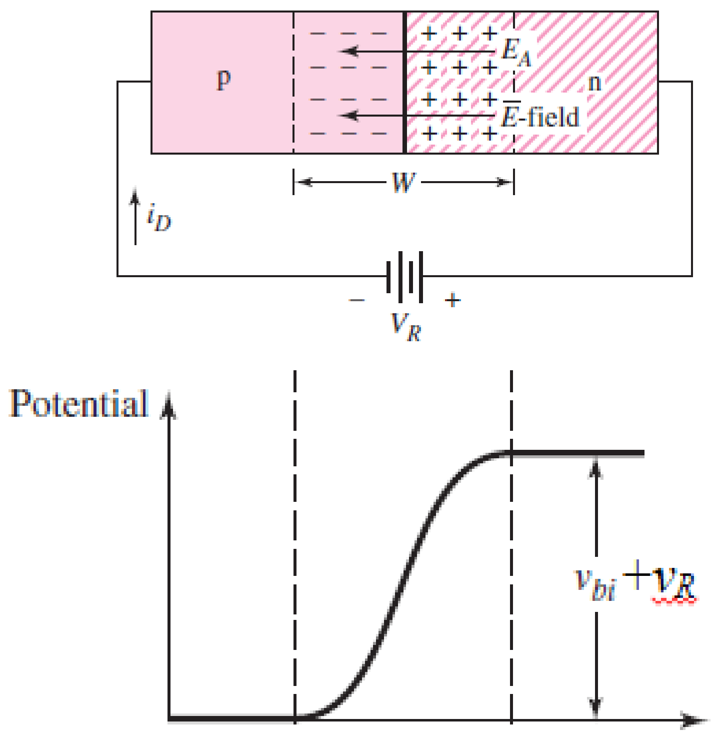
  → against further diffusion of majority carriers.

  → small I_{diff} (sensitive to V_{bi})
- Minority carriers migrate to edges of space-charge region and be swept through.

  → small I_{drift} (depends weekly on temperature)

$$i_D \equiv I_{\text{diff},0} - I_{\text{drift},0} = 0$$

pn-Junction in Reverse Bias



The applied electric field E_A is along the space-charge field E_{field}.

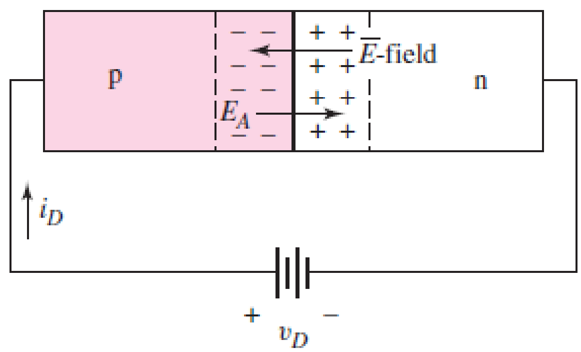
$\rightarrow$ depletion region width increases, potential barrier is higher

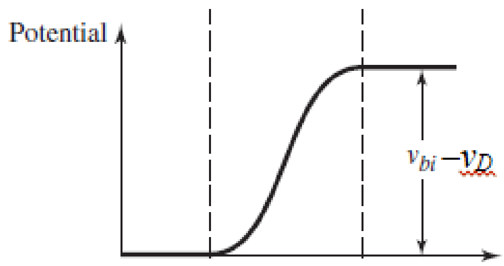
$\rightarrow$ diffusion of majority carriers more difficult

$\rightarrow$ $I_{\text{diff}} \downarrow$ very small (and $I_{\text{drift}} \approx I_{\text{drift},0}$)

$$i_D \equiv I_{\text{diff},0} - I_{\text{drift},0} < 0 \qquad \text{but very small}$$

pn-Junction in Forward Bias





The applied electric field E_A cancels the internal space-charge filed E_{field}.

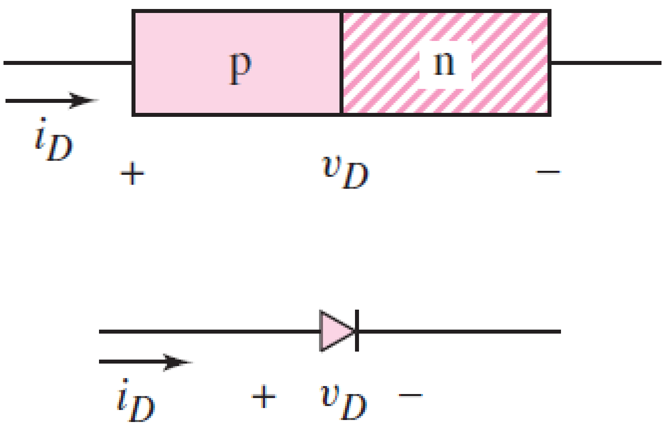
$\rightarrow$ depletion region width decreases, potential barrier is lower

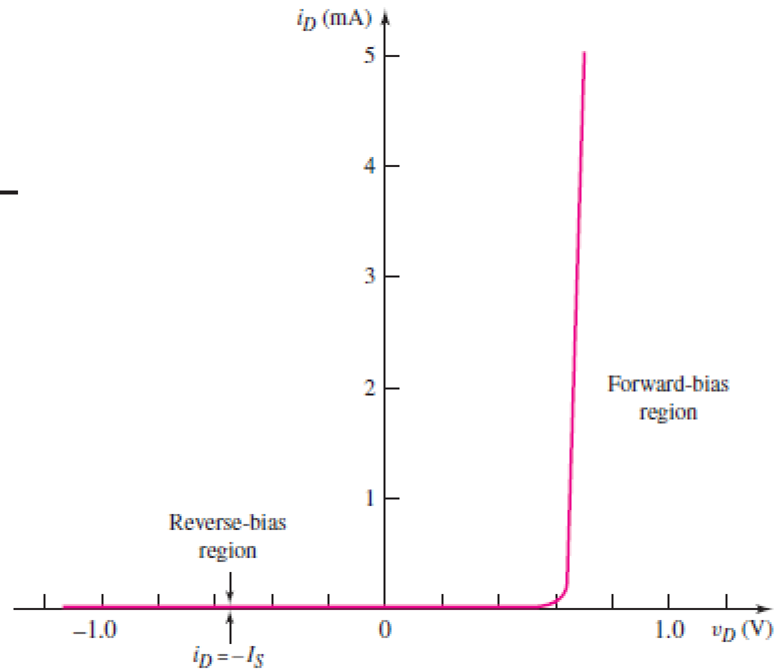
$\rightarrow$ diffusion of majority carriers easier

$\rightarrow$ $I_{\text{diff}} \uparrow$ very large (and $I_{\text{drift}} \approx I_{\text{drift,0}}$)

$$i_D \equiv I_{\text{diff,0}} - I_{\text{drift,0}} > 0 \qquad \text{(very large)}$$

pn Junction Diode Device Law
(Current-Voltage Relationship)





Diode is a two-terminal device with a nonlinear I-V relationship.

$$i_D = I_S\left[e^{\left(\frac{v_D}{V_T}\right)} - 1\right]$$

Diode power $\qquad p_D = v_D i_D$

Reverse-Bias Breakdown

When V_R is too large, the electric field in the space-charge region increases.

- Zener effect:

  Covalent bonds are broken by the electric field and electron-hole pairs are created in the space-charge region.

  $\rightarrow$ large reverse bias current.

- Avalanche effect:

  Minority carriers crossing the space-charge region gain sufficient energy to break covalent bonds during collision process; the generated electron-hole pairs can further be involved in collision process to generate additional electron-hole pairs.

  $\rightarrow$ large reverse bias current.

The reverse-bias current under breakdown is limited by the external circuit.

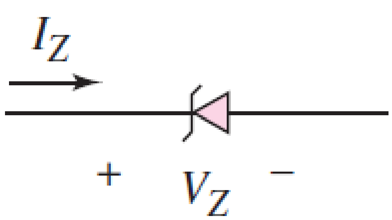
Typical breakdown voltage (peak inverse voltage, PIV):

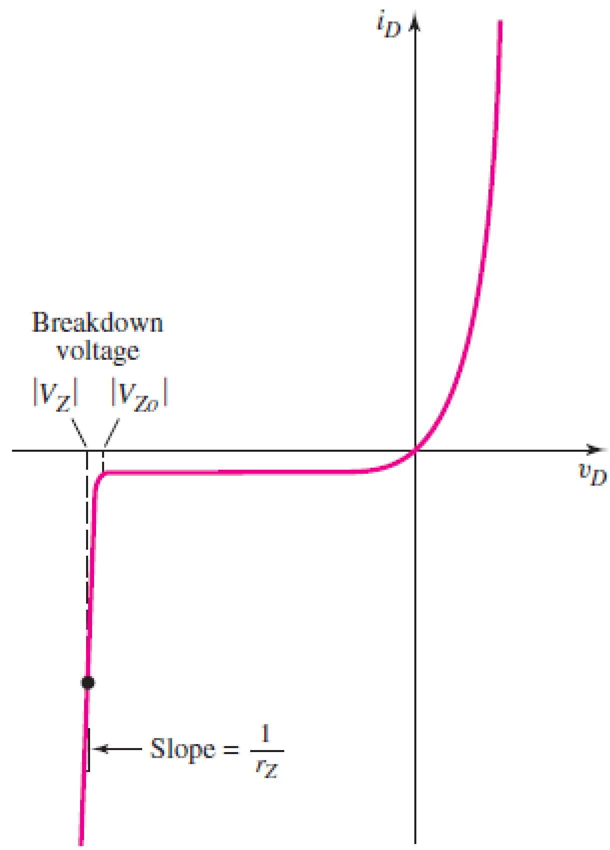
50–200 V;   > 1000 V is possible.

Zener Diode

Diodes with specified reverse breakdown voltage can be designed and fabricated.

Under reverse bias





$$V_Z = -V_D$$

$$I_Z = -I_D$$

- V_{Z0} is the reverse-bias voltage at which the reverse breakdown begins.
- I_Z is reverse-bias current and is limited by the external circuit; avoid heating and catastrophic failure.
- Before reverse-breakdown (including forward-bias), Zener diode is a regular diode.

Zener diode is used in constant-voltage reference circuit.

Diode Circuits: DC Analysis and Models

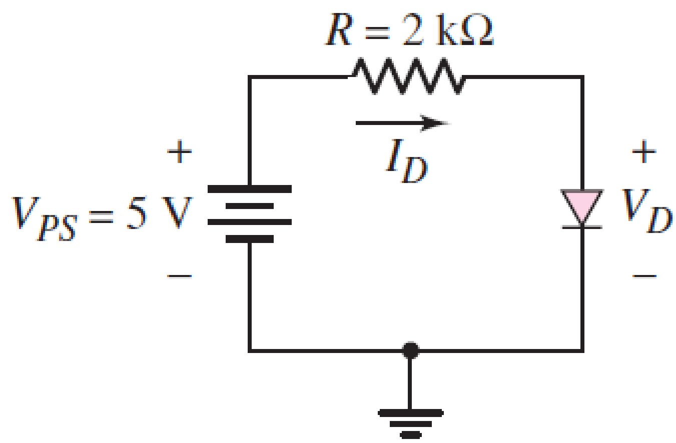
Iteration and Graphical Analysis Techniques

KVL:

$$V_{PS} = RI_D + V_D$$

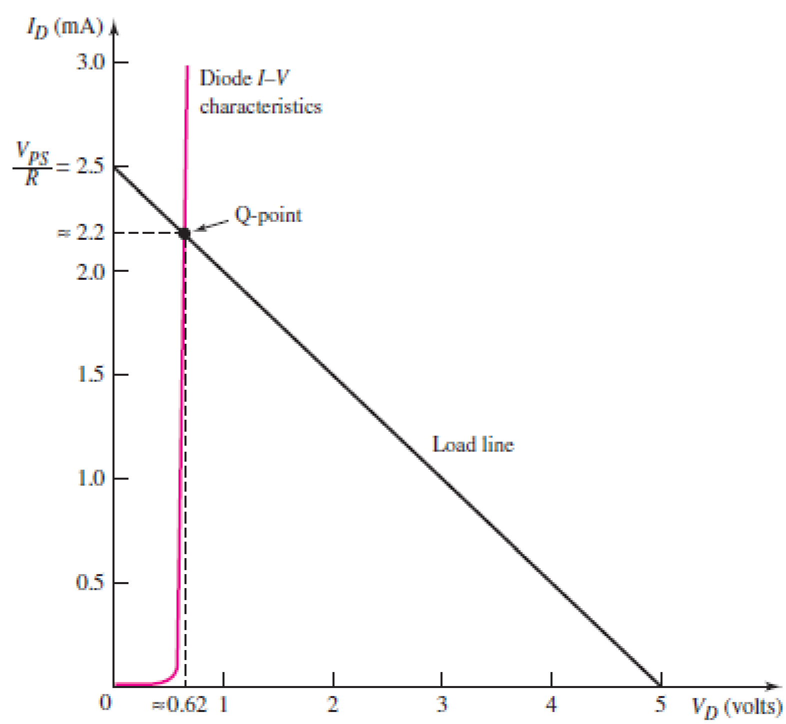
Diode law:

$$I_D = I_S\left[e^{\left(\frac{V_D}{V_T}\right)} - 1\right]$$



1. Iteration approach

2. Graphical approach



3. Computer Simulation Analysis
   PSpice and other simulation softwares.

Piecewise Linear Models

(simplified diode device law)

Approximate the nonlinear current-voltage relationship using several (two) linear relationships.

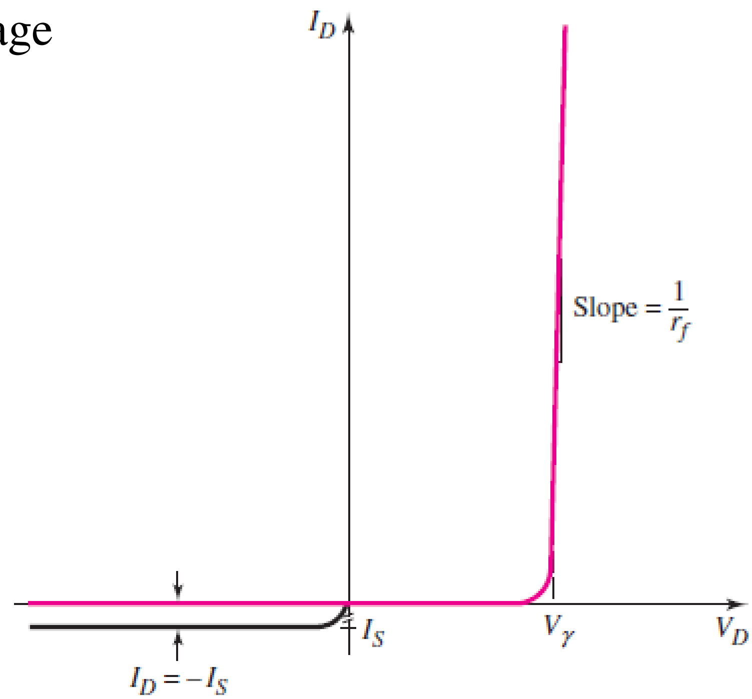
V_γ --- approximate turn-on voltage

r_f --- diode forward resistance

$v_D < V_\gamma$: $\quad i_D = 0$

$v_D > V_\gamma$: $\quad i_D = (v_D - V_\gamma)/r_f$

or $\quad v_D = V_\gamma + r_f i_D$



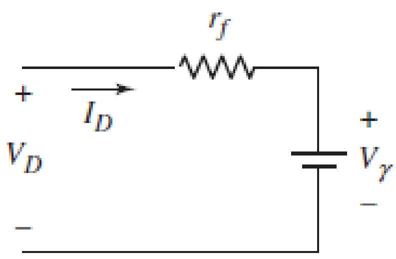
$V_\gamma \sim 0.6 - 0.7$ V for silicon

$r_f \sim 10\ \Omega$

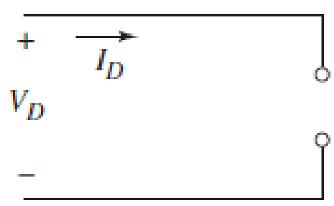
Versions of piecewise linear models

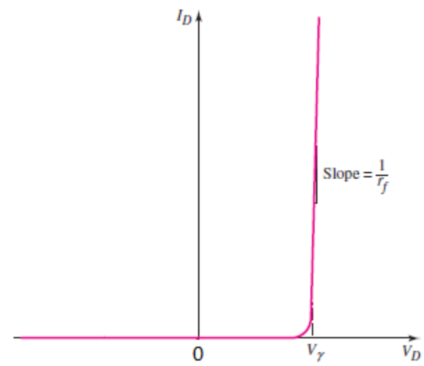
- $V_\gamma \neq 0, \;\; r_f \neq 0$

$v_D > V_\gamma$, on



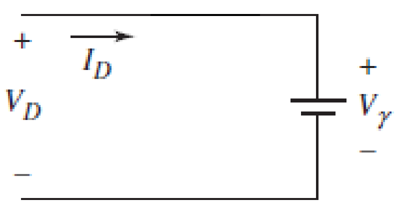
$v_D < V_\gamma$, off



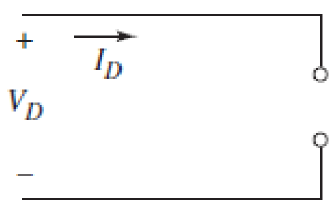


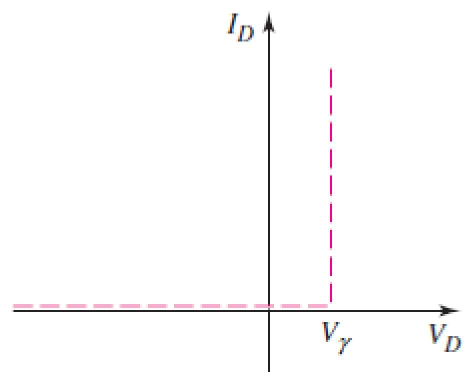
- $V_\gamma \neq 0, \;\; r_f = 0$

$v_D > V_\gamma$, on



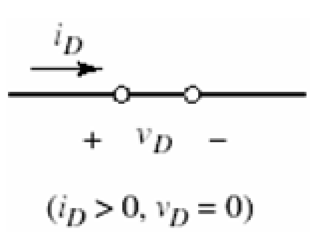
$v_D < V_\gamma$, off



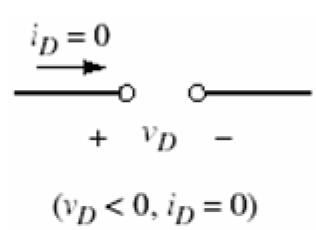


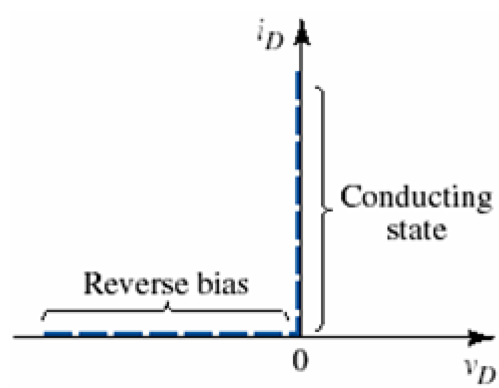
- $V_\gamma = 0, \;\; r_f = 0$ (ideal diode)

$v_D > V_\gamma$, on



$v_D < V_\gamma$, off

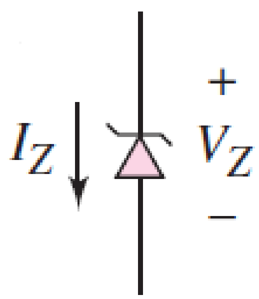


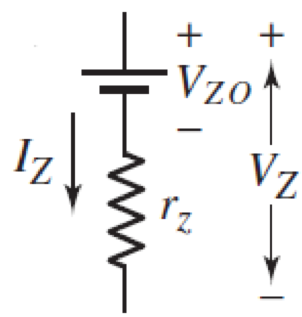


Zener diode model (device law)

Before reverse-breakdown: just like a regular diode.

Under reverse-breakdown:





$V_Z = -V_D \quad I_Z = -I_D$

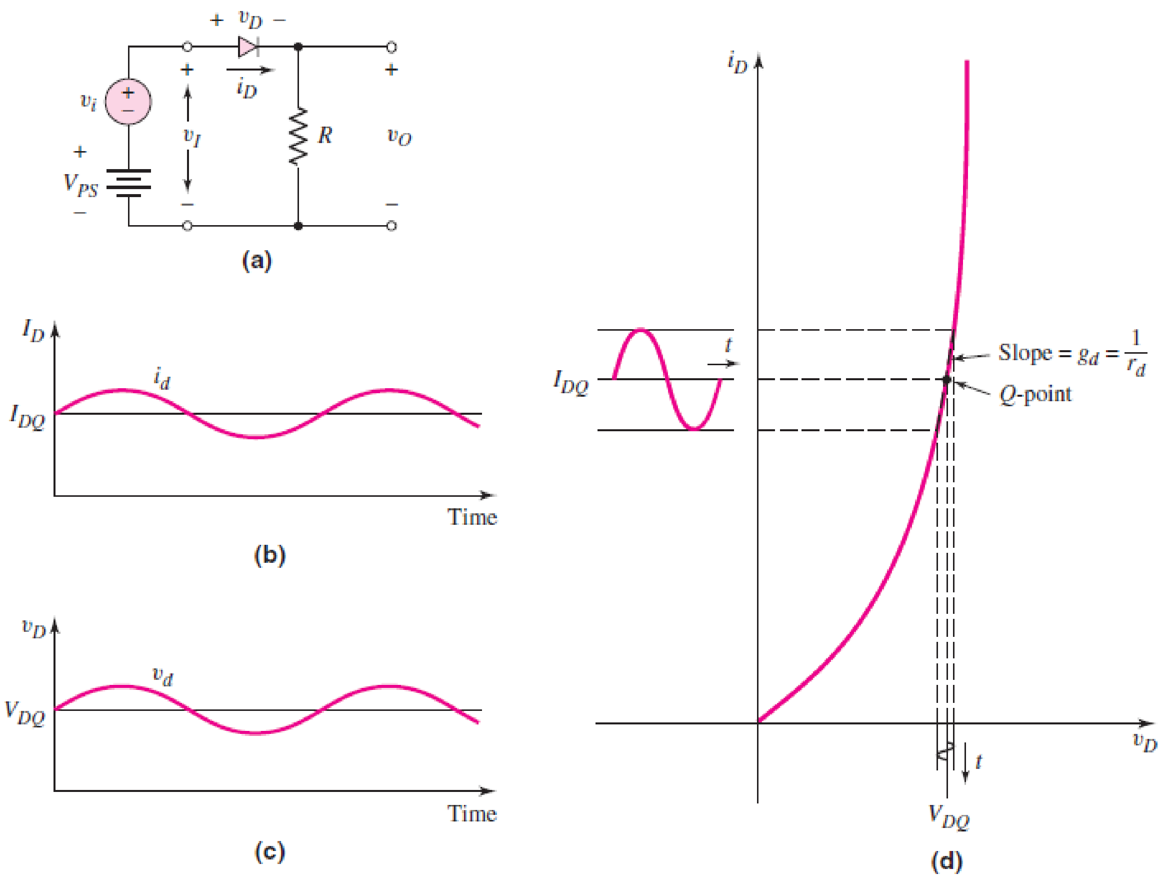
$V_Z = V_{Z0} + r_Z I_Z$

Zener diode power (under reverse breakdown)

$$P_Z = V_Z I_Z = (V_{Z0} + r_Z I_Z) I_Z$$

Diode Circuits: AC Analysis and Equivalent Circuit

Small Signal Analysis



The circuit is biased such that a small ac signal is superimposed on the quiescent point.

Full signal	$i_D(t)$	
DC signal	I_D	
AC signal	$i_d(t)$	(assume to be small)

$$v_D(t) = V_{DQ} + v_d(t)$$

$$i_D(t) = I_{DQ} + i_d(t)$$

AC Diode device law (AC model)

$$i_D = I_S\left[e^{\left(\frac{v_D}{V_T}\right)} - 1\right] \cong I_S e^{\left(\frac{v_D}{V_T}\right)} = I_{DQ} + \Delta i_D$$

$$I_{DQ} = I_S e^{\frac{V_{DQ}}{V_T}}$$

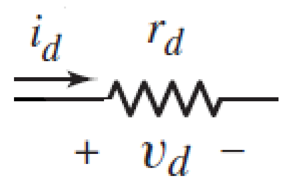
$$\Delta i_D \cong \left.\frac{\partial i_D}{\partial v_D}\right|_Q \Delta v_D \qquad \text{(to 1}^{\text{st}}\text{ order)}$$

Call diode small-signal resistance

$$\frac{1}{r_d} \equiv \left.\frac{\partial i_D}{\partial v_D}\right|_Q = \frac{I_{DQ}}{V_T}$$

Since $\Delta i_D = i_d, \quad \Delta v_D = v_d$

$\rightarrow$ $v_d = r_d i_d$



Superposition of DC and AC Signals

Full signal = DC signal + AC signal

Full circuit ⇒ DC circuit (bias) and AC circuit

Full analysis ⇒ DC analysis and AC analysis

KVL (full): $V_{PS} + v_i(t) = v_D(t) + Ri_D(t)$

$$= \left(V_{DQ} + v_d\right) + R\left(I_{DQ} + i_d\right)$$

DC analysis:

KVL (dc): $V_{PS} = V_{DQ} + RI_{DQ}$

Diode device law (dc): $V_{DQ} = V_\gamma + r_f I_{DQ}$

$$\Rightarrow \quad I_{DQ} = \frac{V_{PS} - V_\gamma}{R + r_f}$$

AC analysis:

KVL (dc): $v_i = v_d + Ri_d$

Diode device law (dc): $v_d = r_d i_d$

$$\Rightarrow \quad i_d = \frac{v_i}{R + r_d}$$

Diode Capacitances

- Junction capacitance, C_j
  (depletion capacitance)

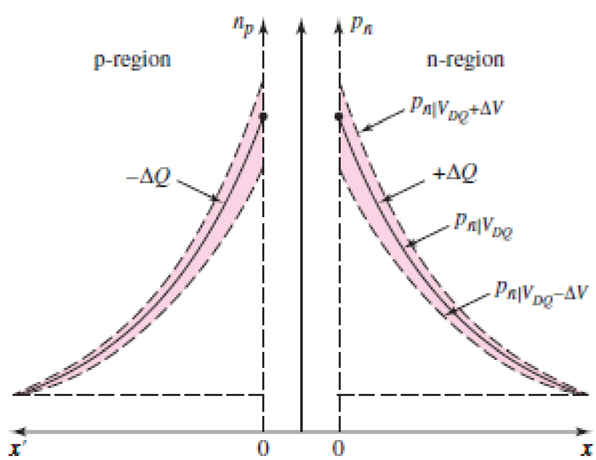
(important under reverse bias, related to the space-charge in the depletion region.)

$V_R \uparrow\downarrow$ space-charge $\uparrow\downarrow$ space-charge region width $\uparrow\downarrow$

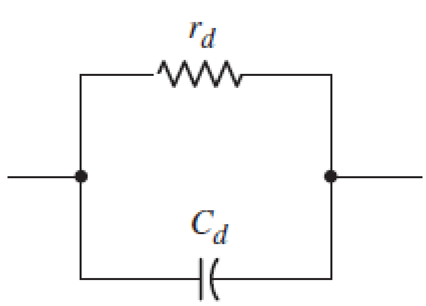
$\Rightarrow$ a capacitor is associated with the pn-junction (depletion region)

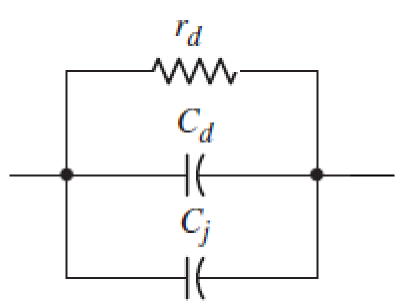
- Diffusion capacitance, C_d

(important under forward bias, related to majority carrier charges diffused into the opposite *p*- and *n*-regions)



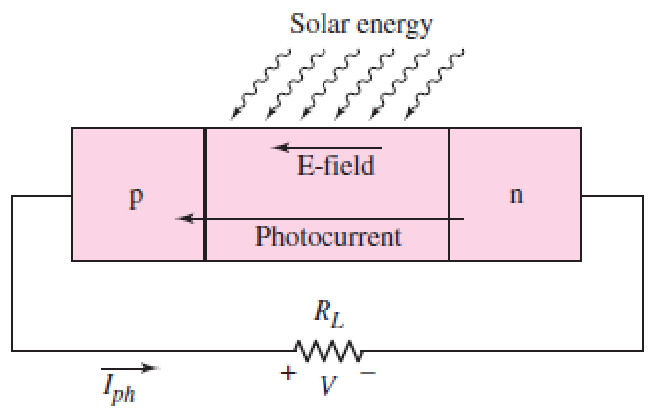
$V_F \uparrow\downarrow$ this charge $\uparrow\downarrow$





Other Diode Types

Solar Cell



Light hits the space charge region and generates electrons and holes that are quickly separated and swept out by the electric field.

⇒ creating a photocurrent and producing a voltage across the load resistor.

Photodiode

Photodiode converts light into electric signal. The pn junction is reverse-biased. Absorbed photons generate electrons and holes in the space-charge region.

⇒ creating a photocurrent proportional to the light intensity.

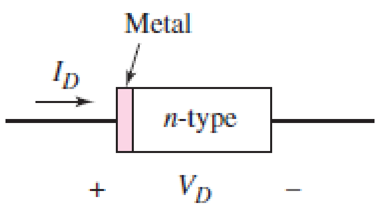
Light-Emitting Diode (LED)

LED converts current into light. In a direct bandgap material (GaAs), under forward-bias, excess electron and hole can recombine in a neutral semiconductor region to emit a photon.

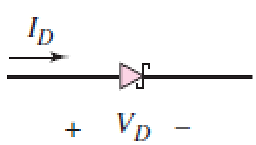
The light intensity is proportional to the diode current.

Schottky Barrier Diode

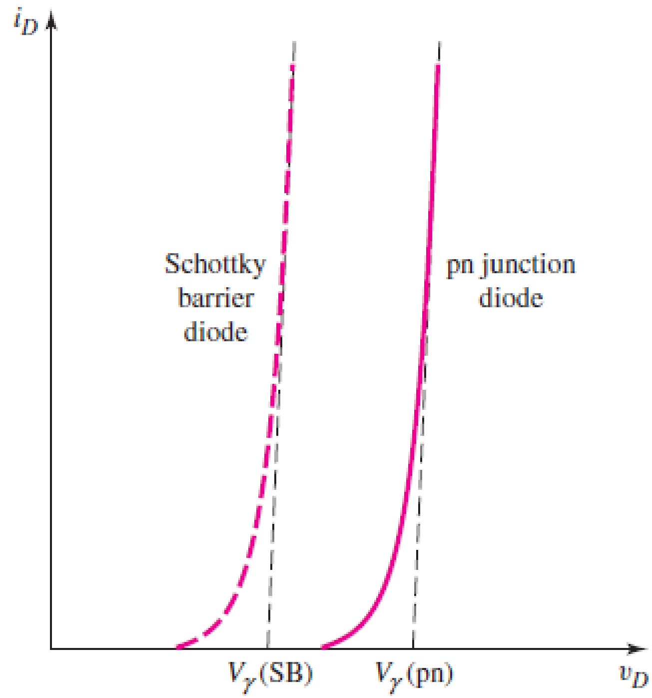
Bonding a metal to a *moderately* doped n-type semiconductor.



(a)



(b)



- Current-voltage characteristics similar to pn-junction.
- Current is from flow of (majority) electrons from n-region to metal; no minority carrier storage.
  $\rightarrow$ capacitance is very small and switching time is very fast.
- Large I_s and small turn-on voltage ($V_\gamma \approx 0.3$ V).