

Conductivity and Semi-Conductors

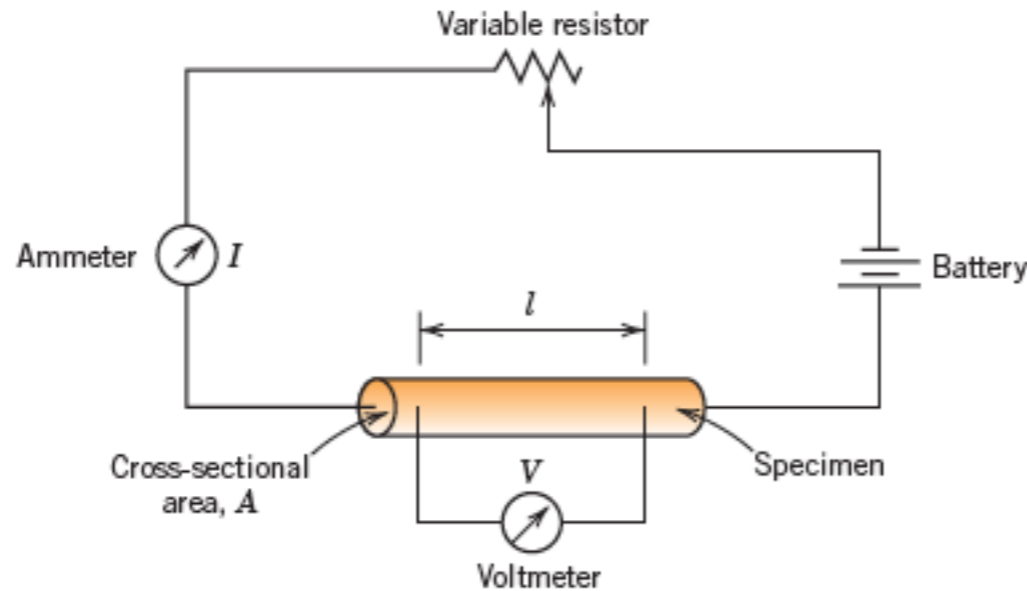


Figure 18.1 Schematic representation of the apparatus used to measure electrical resistivity.

$$V = IR$$

$$\rho = \frac{RA}{l}$$

$$\sigma = \frac{1}{\rho}$$

J = current density = I/A

$$J = \sigma \mathcal{E}$$

E = Electric field intensity = V/l

where l is the distance between two points

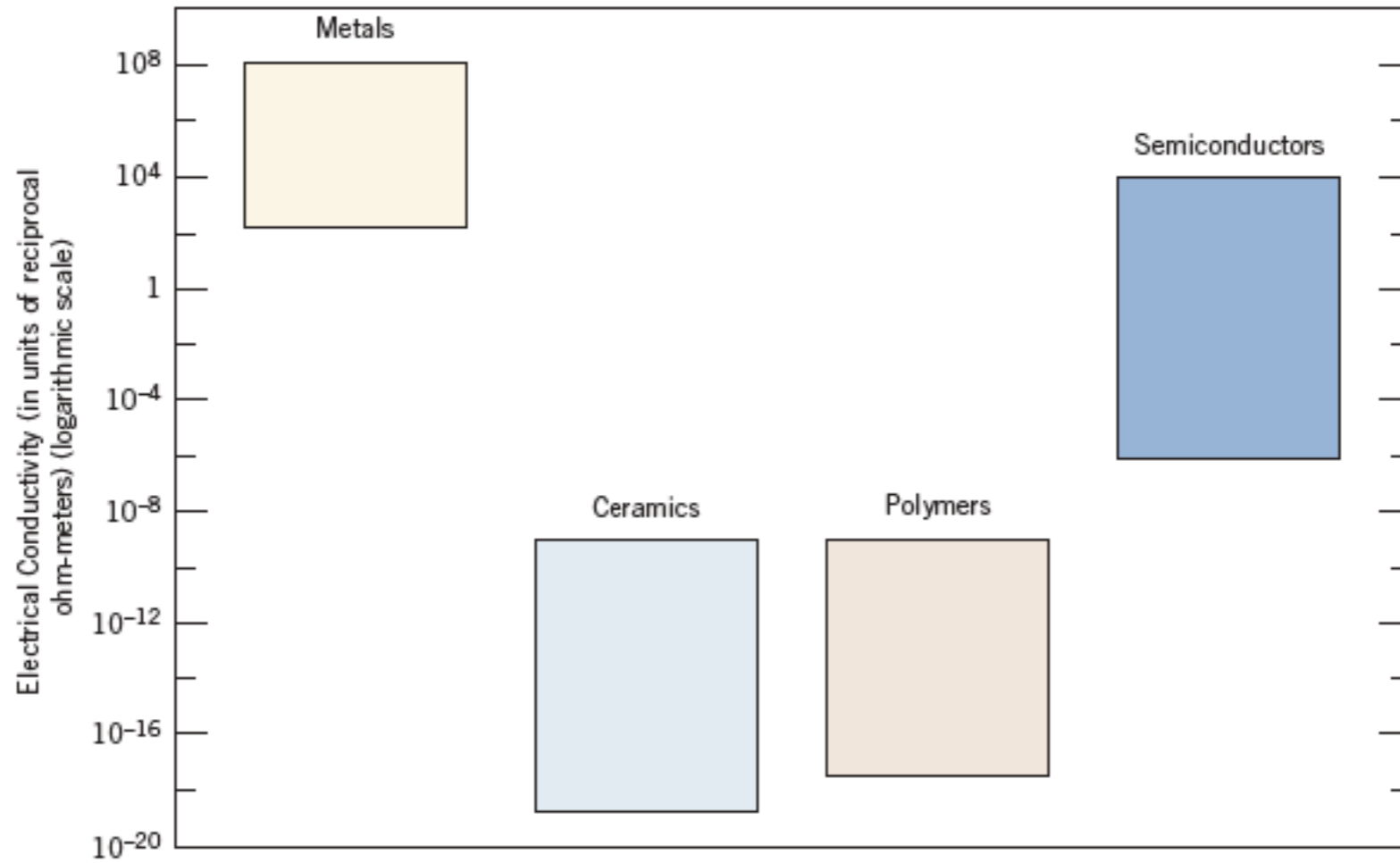
conductors, semiconductors, and insulators.

Metals:

Semiconductors:

Many Polymers and Glasses

Figure 1.7
Bar-chart of room-temperature electrical conductivity ranges for metals, ceramics, polymers, and semiconducting materials.



Electrical Conduction (motion of electrons)
Ionic Conduction (motion of ions)

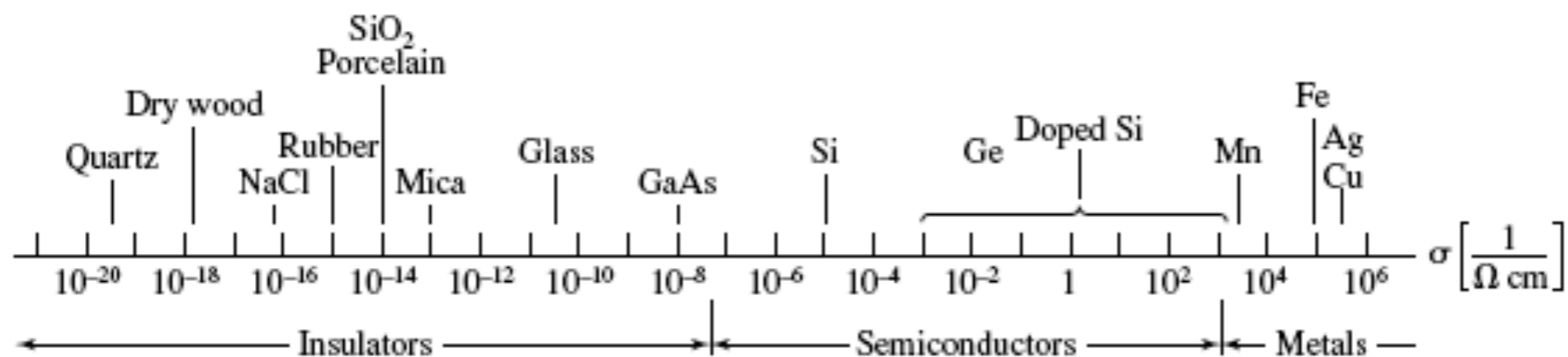


FIGURE 11.1. Room-temperature conductivity of various materials. (Superconductors, having conductivities of many orders of magnitude larger than copper, near 0 K, are not shown. The conductivity of semiconductors varies substantially with temperature and purity.) It is customary in engineering to use the centimeter as the unit of length rather than the meter. We follow this practice. The reciprocal of the ohm (Ω) is defined to be 1 siemens (S); see Appendix II. For conducting polymers, refer to Figure 11.20.

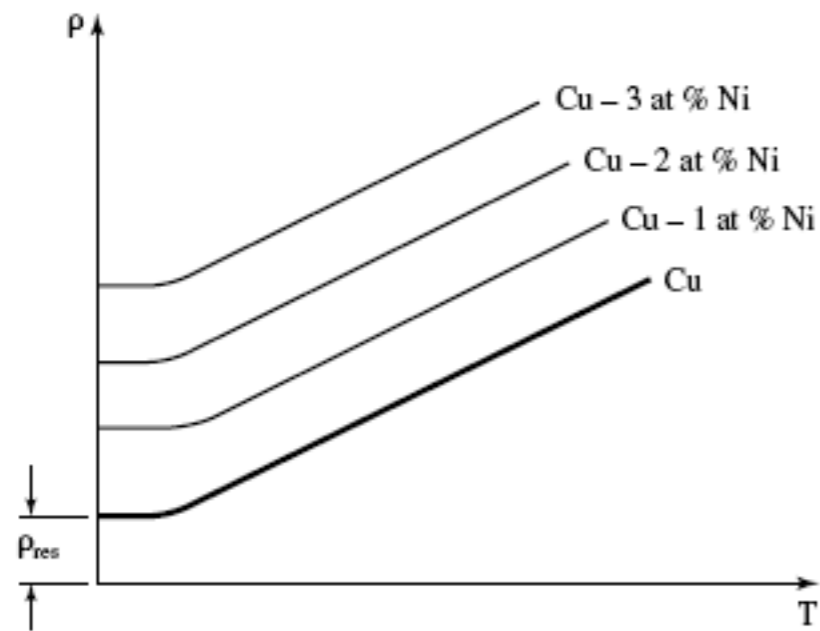


FIGURE 11.3. Schematic representation of the temperature dependence of the resistivity of copper and various copper-nickel alloys. ρ_{res} is the residual resistivity.

$$\rho_2 = \rho_1[1 + \alpha(T_2 - T_1)], \quad (11.7)$$

FIGURE 11.4. Schematic representation of an electron path through a conductor (containing vacancies, impurity atoms, and a grain boundary) under the influence of an electric field. This classical description does not completely describe the resistance in materials.



Free Electron Model

Drude Model (kinetic theory of gasses)

$$m \frac{dv}{dt} + \gamma v = e \cdot \mathcal{E}$$

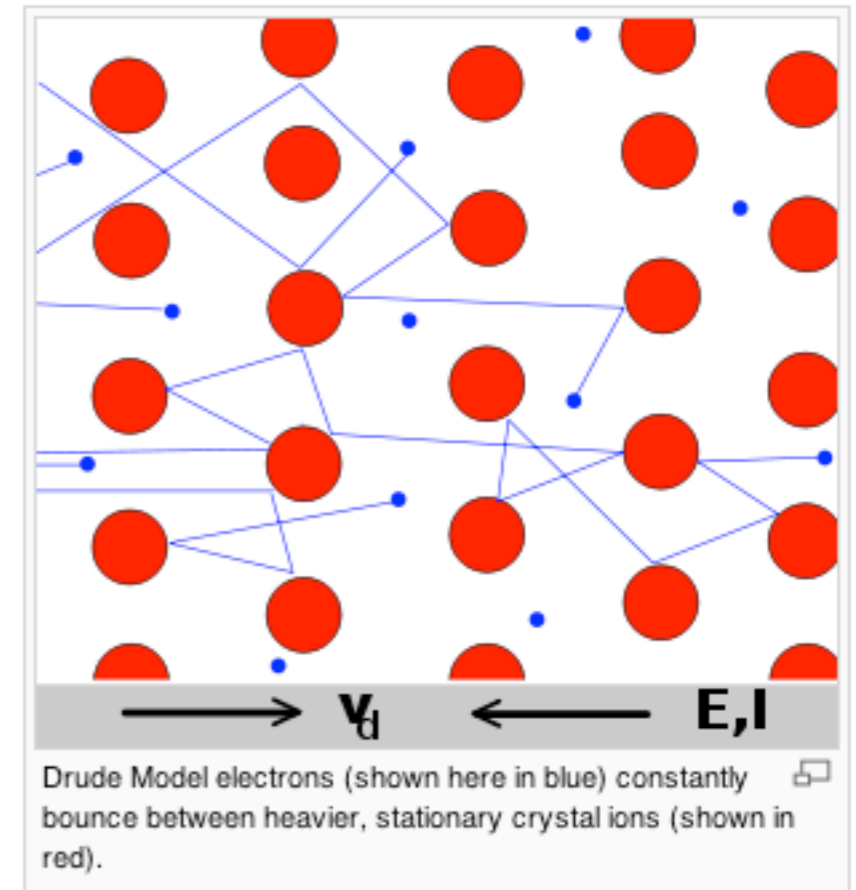
$$\sigma = \frac{N_f \cdot e^2 \cdot \tau}{m},$$

$$\tau = m/\gamma$$

$$\sigma(\omega) = \frac{\sigma_0}{1 + i\omega\tau}. \quad \text{For AC}$$

Drude-Sommerfeld Model

Include quantum mechanics
(wave nature of electron)



4 Quantum Numbers: Size, Shape, Spatial Orientation, Magnetically Determined Energy State

Principle Quantum Number = n = Distance from Nucleus (Bohr number)

K, L, M, N or 1, 2, 3, 4

Second quantum number = l = Shape

s, p, d, f

n restricts the number of these

Third quantum number = m_l = magnetically distinguishable energy states

Fourth quantum number = m_s = spin moment $+1/2$ or $-1/2$ = up or down orientation

Table 2.1 The Number of Available Electron States in Some of the Electron Shells and Subshells

Principal Quantum Number n	Shell Designation	Subshells	Number of States	Number of Electrons	
				Per Subshell	Per Shell
1	K	s	1	2	2
2	L	s	1	2	8
		p	3	6	
3	M	s	1	2	18
		p	3	6	
		d	5	10	
4	N	s	1	2	32
		p	3	6	
		d	5	10	
		f	7	14	

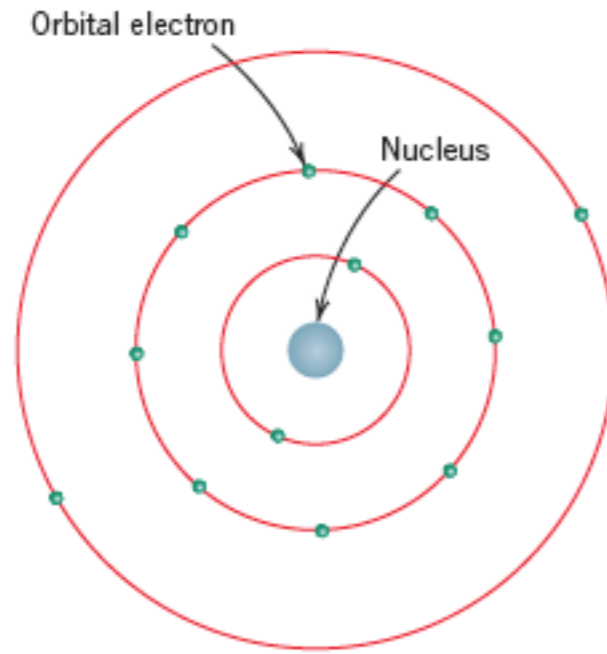


Figure 2.1 Schematic representation of the Bohr atom.

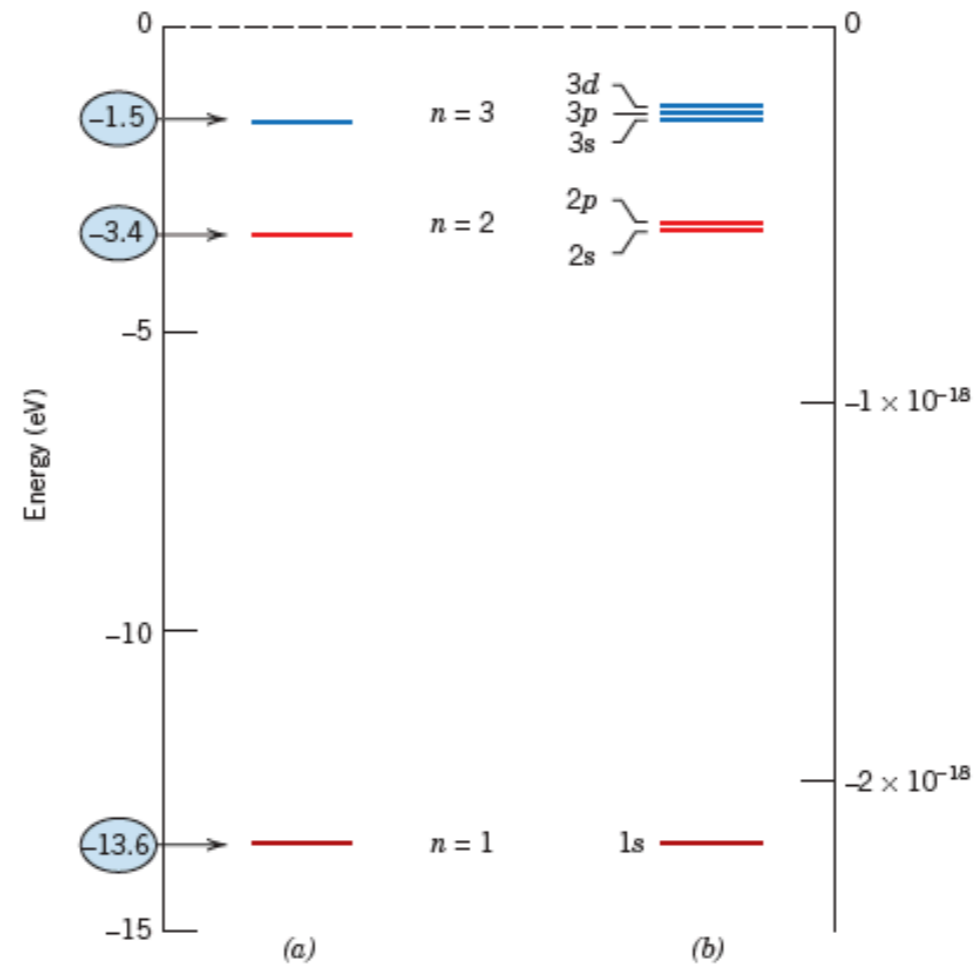


Figure 2.2 (a) The first three electron energy states for the Bohr hydrogen atom (b) Electron energy states for the first three shells of the wave-mechanical hydrogen atom. (Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 10. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

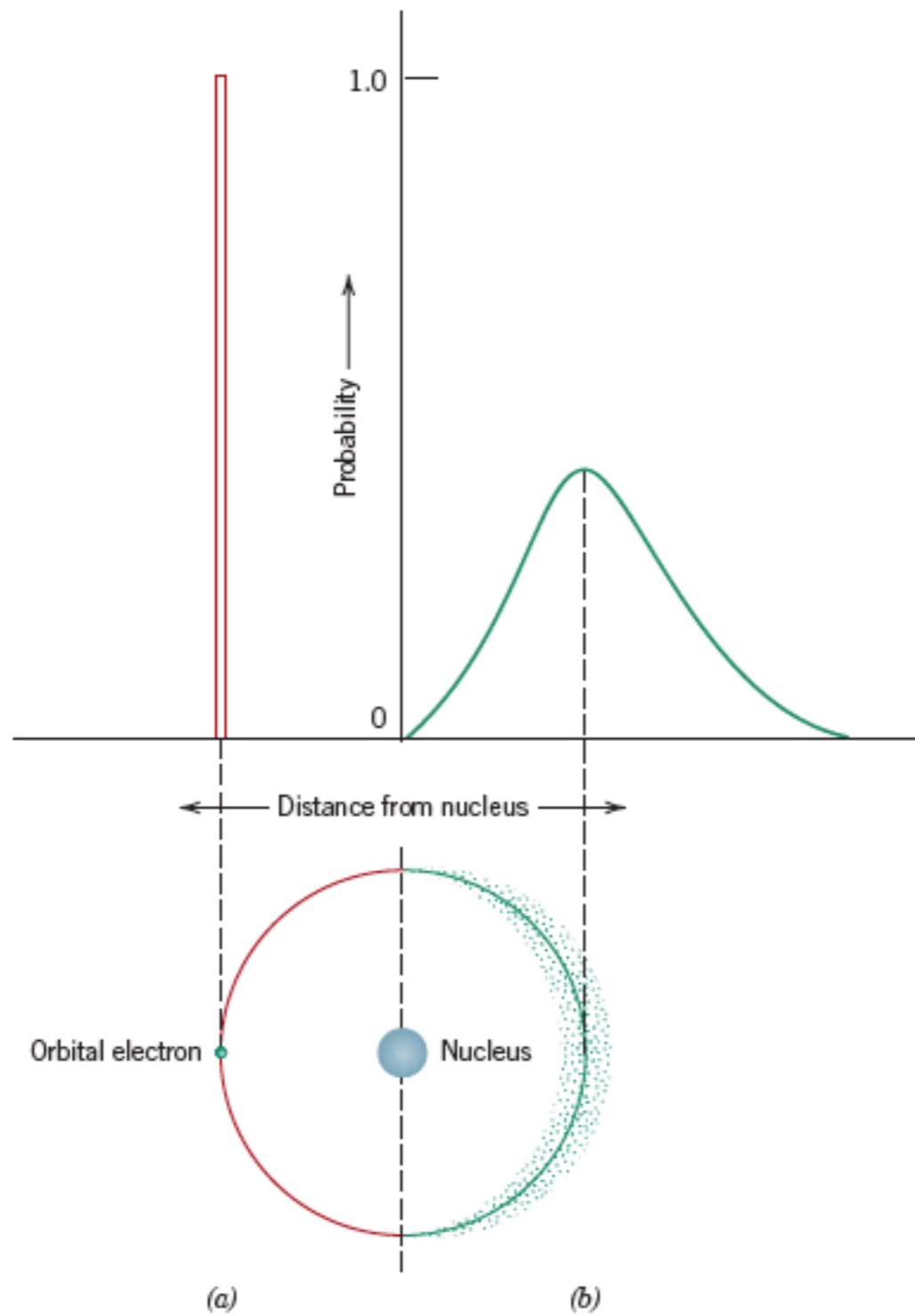


Figure 2.3 Comparison of the (a) Bohr and (b) wave-mechanical atom models in terms of electron distribution. (Adapted from Z. D. Jastrzebski, *The Nature and Properties of Engineering Materials*, 3rd edition, p. 4. Copyright © 1987 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Primary quantum numbers distinguished by energy

Different primary quantum number states can have overlapping energy levels.

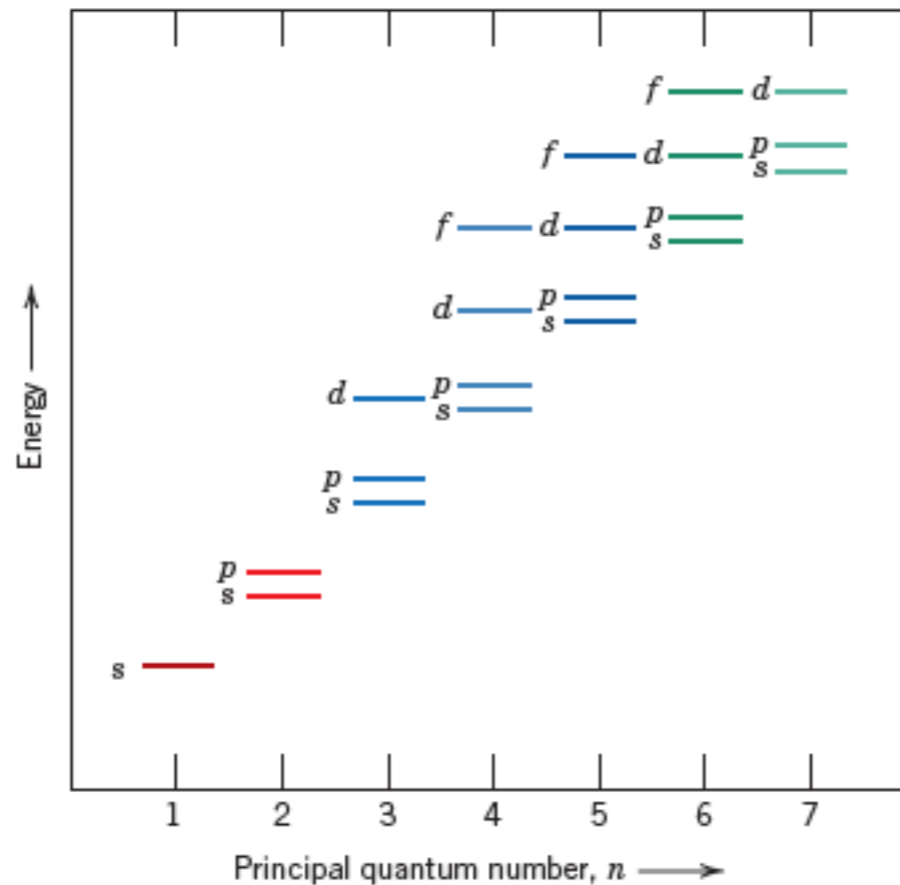


Figure 2.4 Schematic representation of the relative energies of the electrons for the various shells and subshells. (From K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*, p. 22. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

for each individual atom there exist discrete energy levels that may be occupied by electrons, arranged into shells and subshells. Shells are designated by integers (1, 2, 3, etc.), and subshells by letters (*s*, *p*, *d*, and *f*). For each of *s*, *p*, *d*, and *f* subshells, there exist, respectively, one, three, five, and seven states. The electrons in most atoms fill only the states having the lowest energies, two electrons of opposite spin per state, in accordance with the Pauli exclusion principle. The electron configuration of an isolated atom represents the arrangement of the electrons within the allowed states.

Density of States $Z(E)$

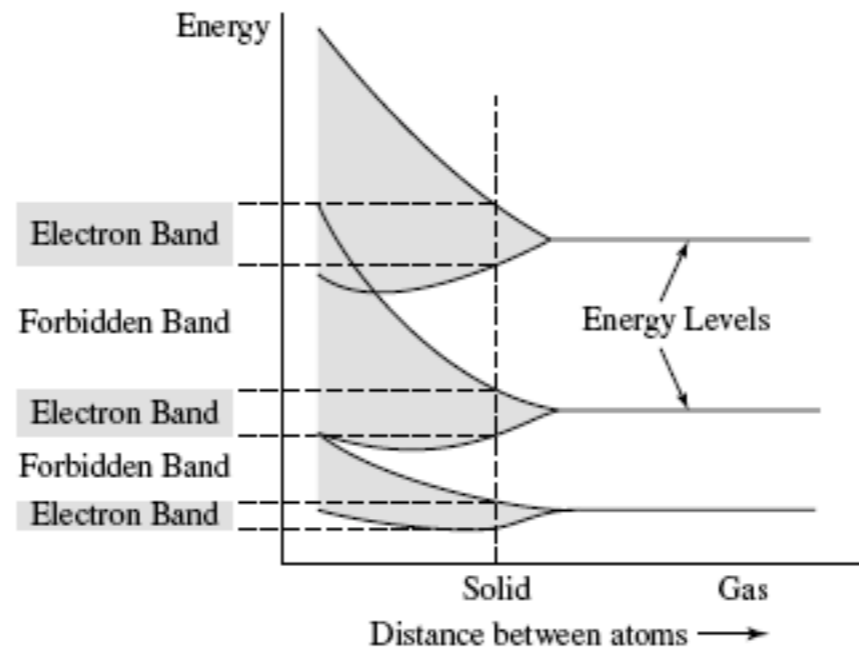
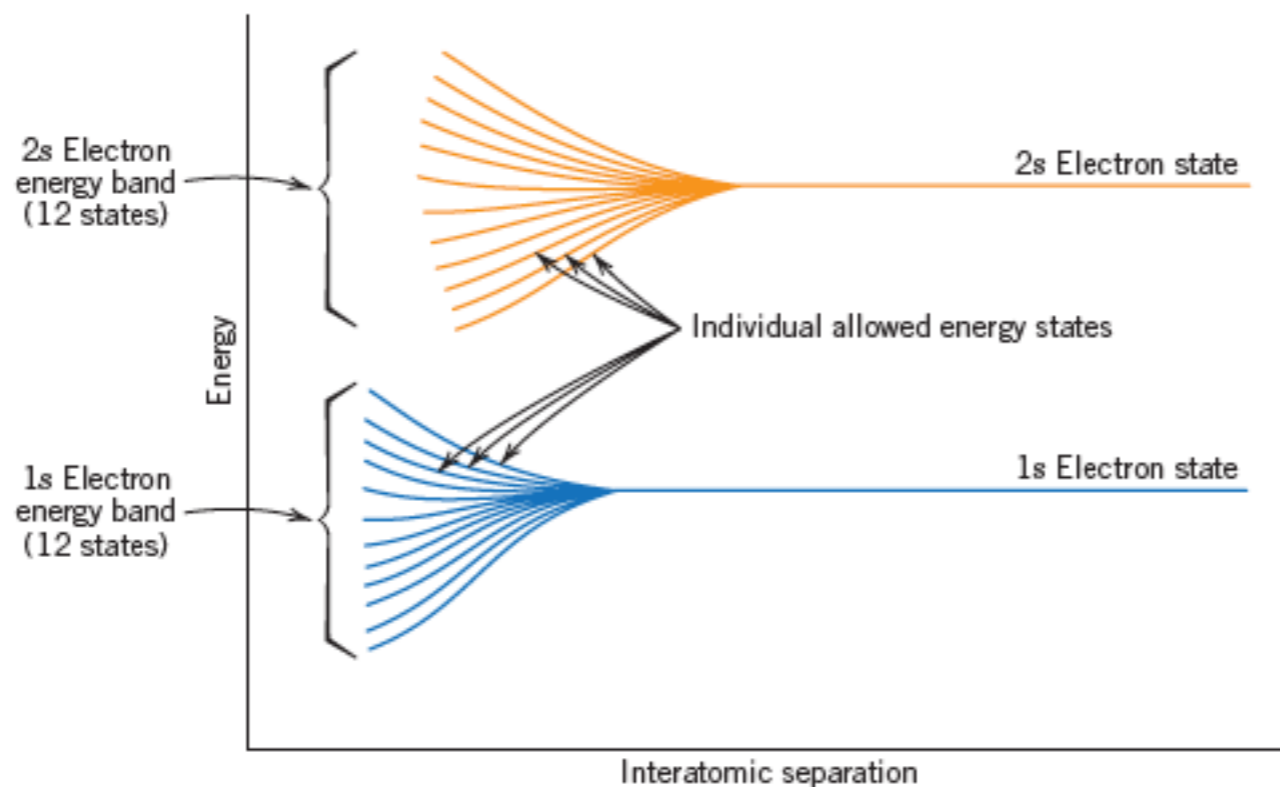


FIGURE 11.5. Schematic representation of energy levels (as for isolated atoms) and widening of these levels into energy bands with decreasing distance between atoms. Energy bands for a specific case are shown at the left of the diagram.

Figure 18.2
Schematic plot of electron energy versus interatomic separation for an aggregate of 12 atoms ($N = 12$). Upon close approach, each of the 1s and 2s atomic states splits to form an electron energy band consisting of 12 states.



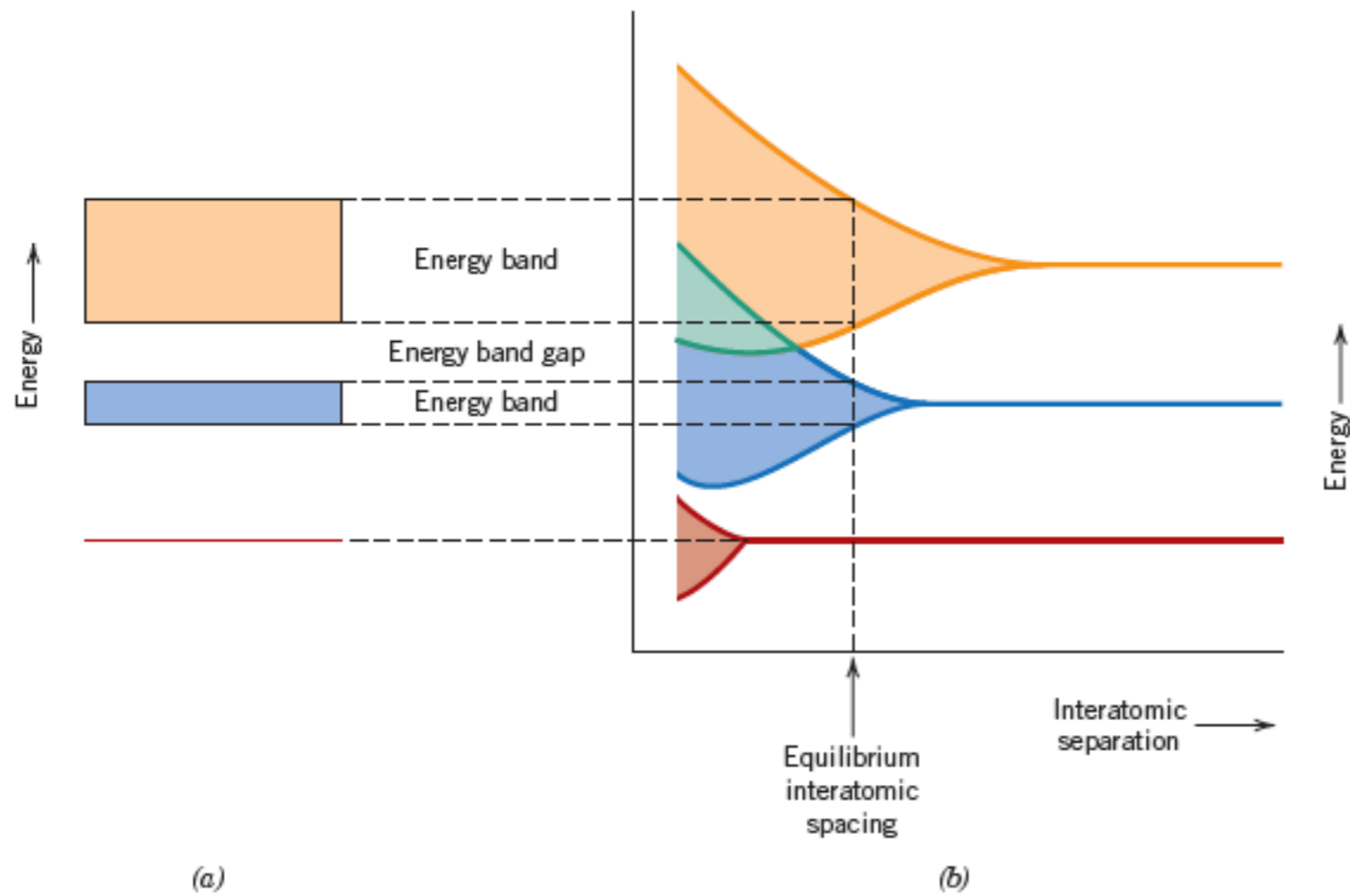


Figure 18.3 (a) The conventional representation of the electron energy band structure for a solid material at the equilibrium interatomic separation. (b) Electron energy versus interatomic separation for an aggregate of atoms, illustrating how the energy band structure at the equilibrium separation in (a) is generated. (From Z. D. Jastrzebski, *The Nature and Properties of Engineering Materials*, 3rd edition. Copyright © 1987 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

The number of states within each band will equal the total of all states contributed by the N atoms. For example, an s band will consist of N states, and a p band of $3N$ states. With regard to occupancy, each energy state may accommodate two electrons, which must have oppositely directed spins. Furthermore, bands will contain the electrons that resided in the corresponding levels of the isolated atoms; for example, a $4s$ energy band in the solid will contain those isolated atom's $4s$ electrons. Of course, there will be empty bands and, possibly, bands that are only partially filled.

The electrical properties of a solid material are a consequence of its electron band structure—that is, the arrangement of the outermost electron bands and the way in which they are filled with electrons.

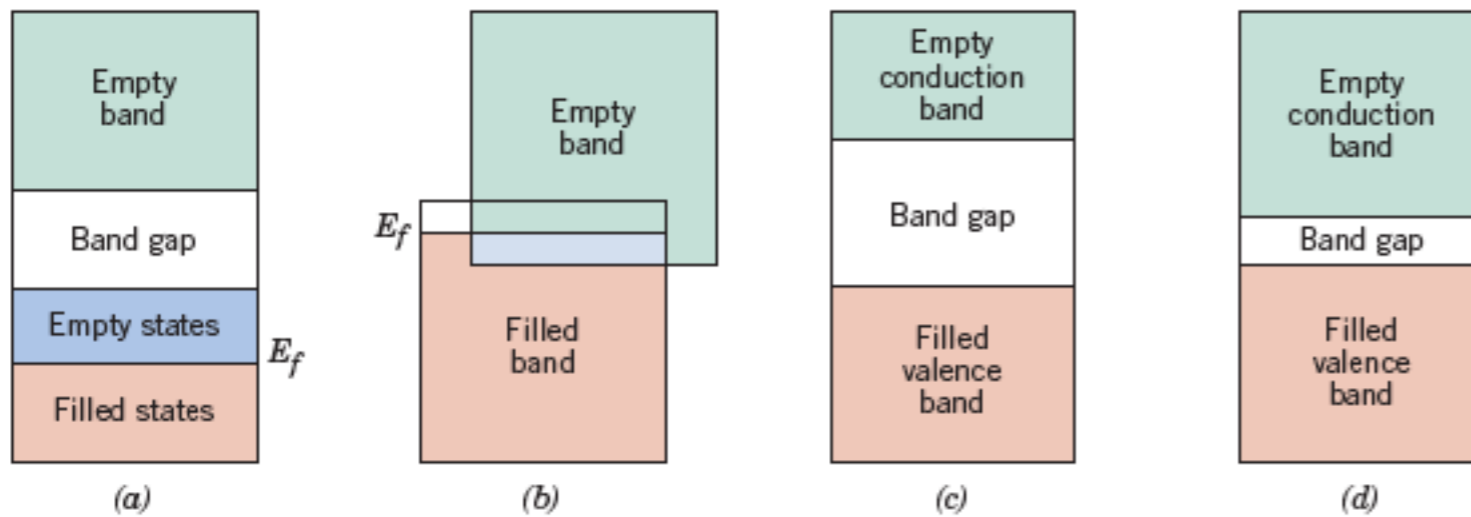


Figure 18.4 The various possible electron band structures in solids at 0 K. (a) The electron band structure found in metals such as copper, in which there are available electron states above and adjacent to filled states, in the same band. (b) The electron band structure of metals such as magnesium, wherein there is an overlap of filled and empty outer bands. (c) The electron band structure characteristic of insulators; the filled valence band is separated from the empty conduction band by a relatively large band gap (>2 eV). (d) The electron band structure found in the semiconductors, which is the same as for insulators except that the band gap is relatively narrow (<2 eV).

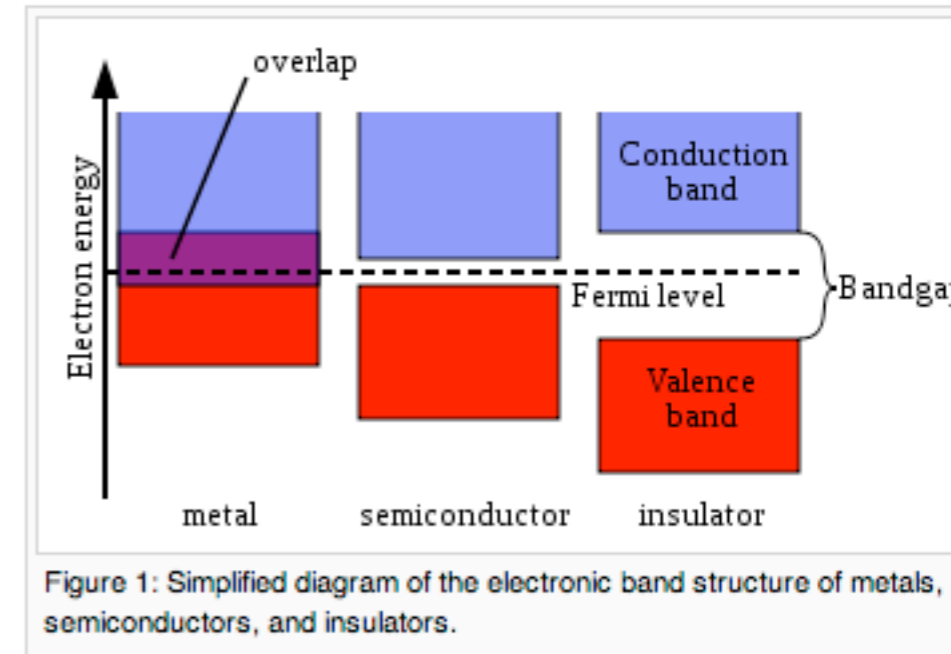


Figure 1: Simplified diagram of the electronic band structure of metals, semiconductors, and insulators.

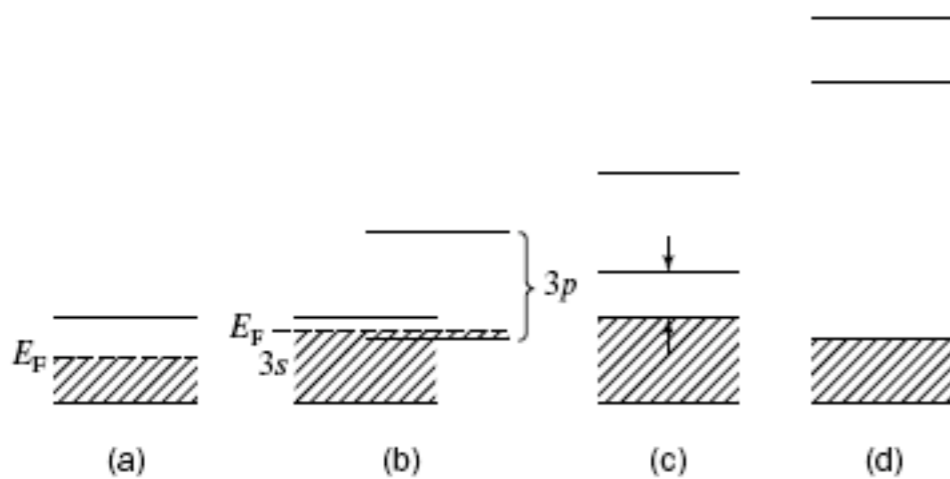


FIGURE 11.6. Simplified representation for energy bands for (a) monovalent metals, (b) bivalent metals, (c) semiconductors, and (d) insulators. For a description of the nomenclature, see Appendix I.

$$\text{Fermi Energy} = E_F$$

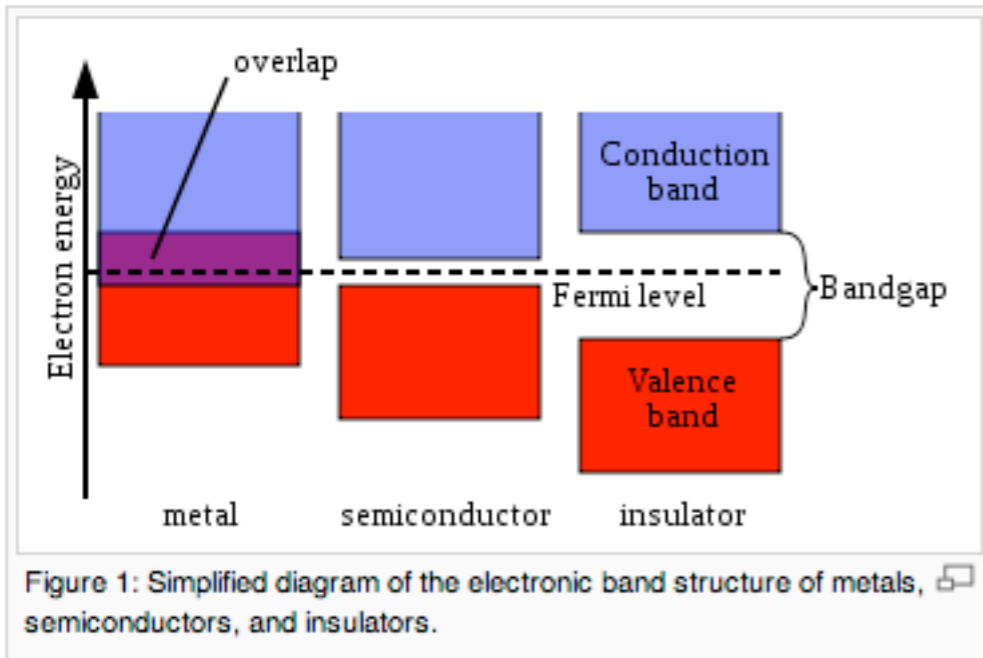
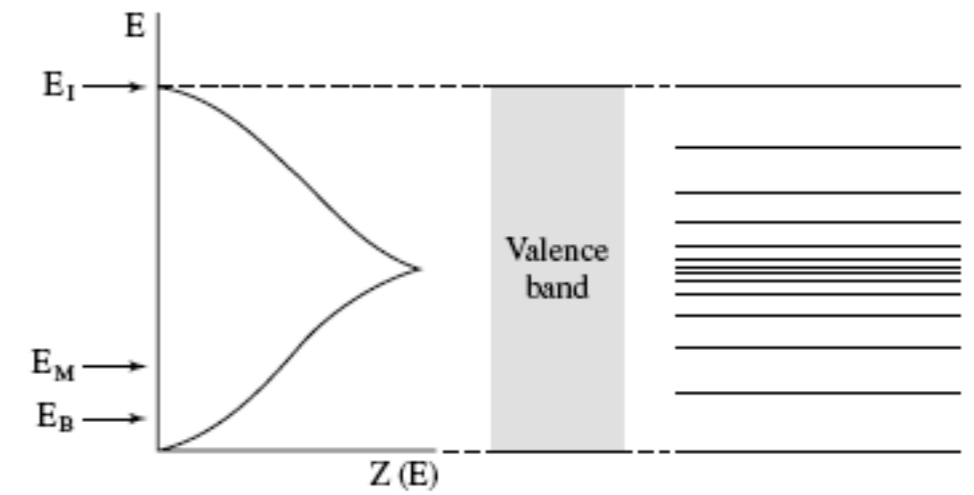


FIGURE 11.7. Schematic representation of the density of electron states $Z(E)$ within an electron energy band. The density of states is essentially identical to the population density $N(E)$ for energies below the Fermi energy, E_F (i.e., for that energy level up to which a band is filled with electrons). Examples of highest electron energies for a monovalent metal (E_M), for a bivalent metal (E_B), and for an insulator (E_I) are indicated.



$$\sigma = \frac{1}{3} e^2 v_F^2 \tau N(E_F)$$

$$\sigma = \frac{N_f \cdot e^2 \cdot \tau}{m}$$

Drude Model

Quantum Mechanics Model
Fermi drift velocity v_F

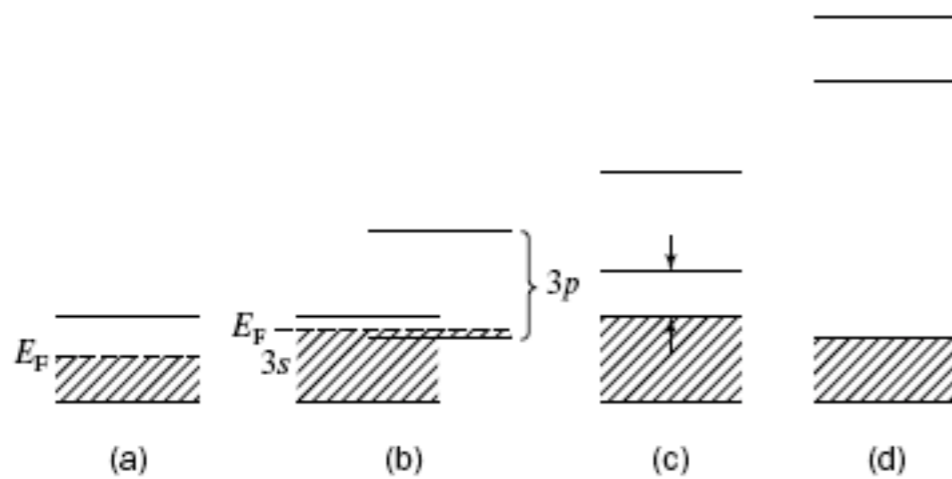
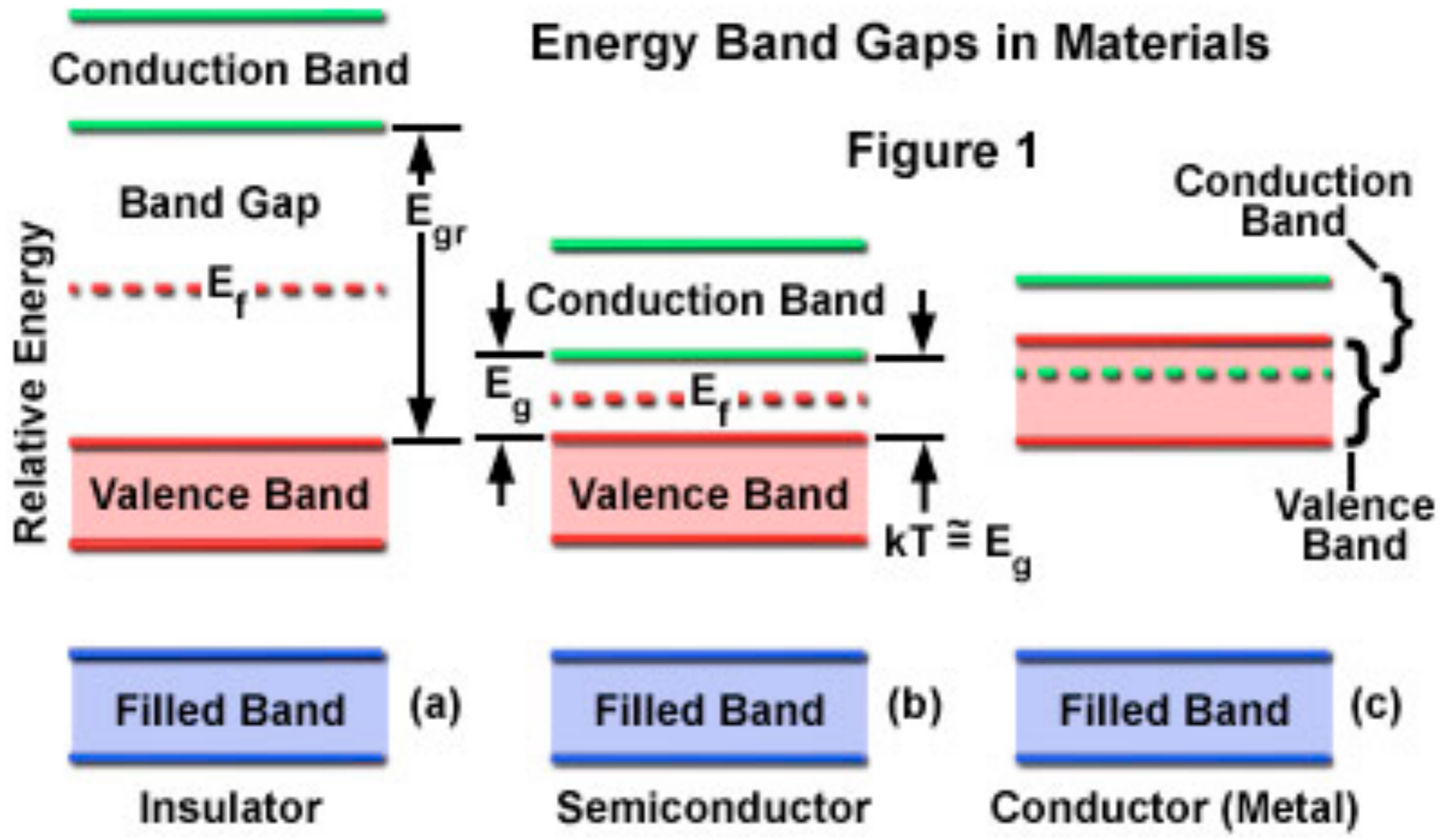
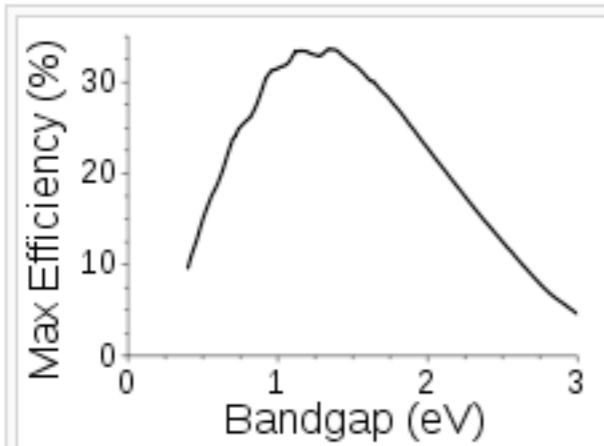


FIGURE 11.6. Simplified representation for energy bands for (a) monovalent metals, (b) bivalent metals, (c) semiconductors, and (d) insulators. For a description of the nomenclature, see Appendix I.

Fermi Energy = E_F



Description of the electronic bands in solids[8].

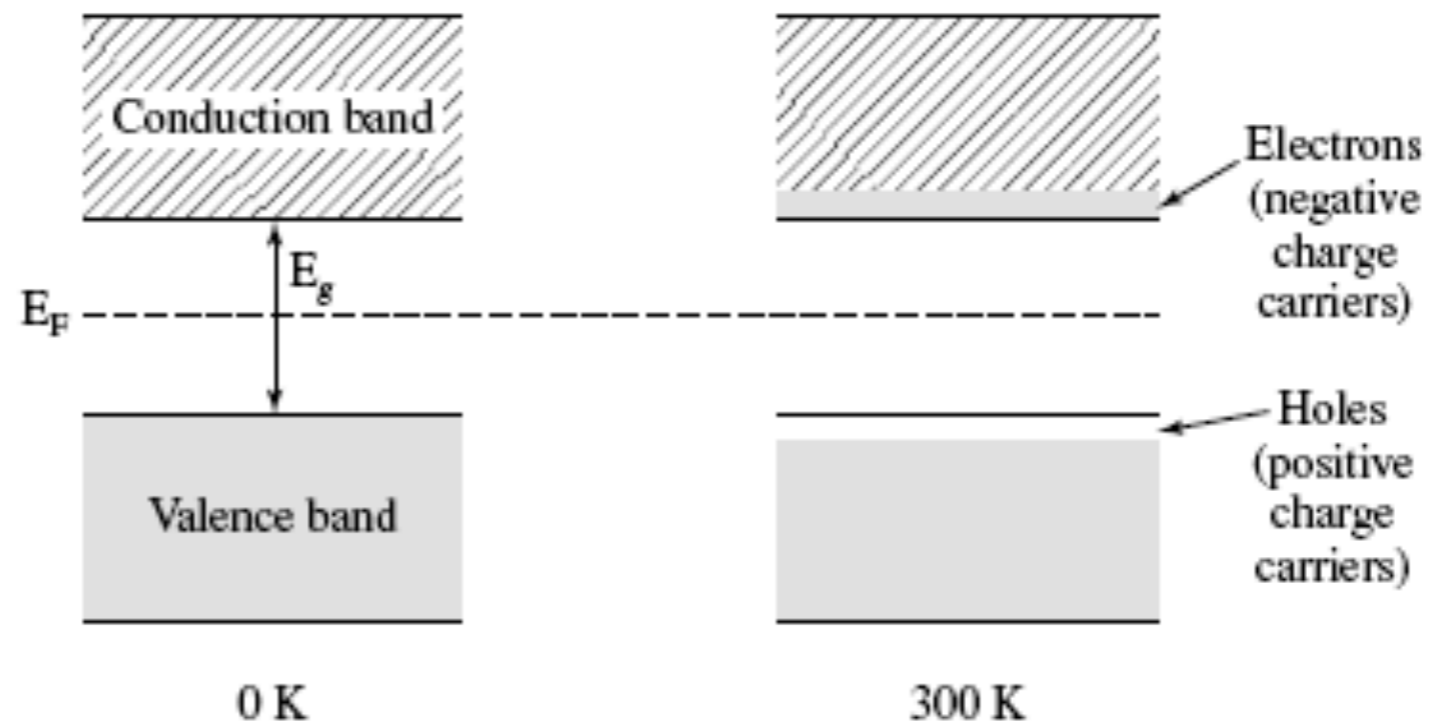


The Shockley–Queisser limit gives the maximum possible efficiency of a single junction solar cell under un-concentrated sunlight, as a function of the semiconductor bandgap. If the bandgap is too high, most daylight photons cannot be absorbed; if it is too low, then most photons have much more energy than necessary to excite electrons across the bandgap, and the rest is wasted. The semiconductors commonly used in commercial solar cells have bandgaps near the peak of this curve, for example silicon (1.1 eV) or CdTe (1.5 eV). The Shockley–Queisser limit can be exceeded by tandem solar cells, concentrating sunlight onto the cell, and other methods.

Material	Symbol	Band gap (eV) @ 302K	Reference
Silicon	Si	1.11	[6]
Selenium	Se	1.74	
Germanium	Ge	0.67	[6]
Silicon carbide	SiC	2.86	[6]
Aluminium phosphide	AlP	2.45	[6]
Aluminium arsenide	AlAs	2.16	[6]
Aluminium antimonide	AlSb	1.6	[6]
Aluminium nitride	AlN	6.3	
Diamond	C	5.5	
Gallium(III) phosphide	GaP	2.26	[6]
Gallium(III) arsenide	GaAs	1.43	[6]
Gallium(III) nitride	GaN	3.4	[6]
Gallium(II) sulfide	GaS	2.5	
Gallium antimonide	GaSb	0.7	[6]
Indium antimonide	InSb	0.17	[6]
Indium(III) nitride	InN	0.7	[7]
Indium(III) phosphide	InP	1.35	[6]
Indium(III) arsenide	InAs	0.36	[6]
Zinc oxide	ZnO	3.37	
Zinc sulfide	ZnS	3.6	[6]
Zinc selenide	ZnSe	2.7	[6]
Zinc telluride	ZnTe	2.25	[6]
Cadmium sulfide	CdS	2.42	[6]
Cadmium selenide	CdSe	1.73	[6]
Cadmium telluride	CdTe	1.49	[8]
Lead(II) sulfide	PbS	0.37	[6]
Lead(II) selenide	PbSe	0.27	[6]
Lead(II) telluride	PbTe	0.29	[6]
Copper(II) oxide	CuO	1.2	[9]
Copper(I) oxide	Cu ₂ O	2.1	[10]
Iron disilicide	β-FeSi ₂	0.87	[11]

Semiconductors

FIGURE 11.11. Simplified band diagrams for an intrinsic semiconductor such as pure silicon at two different temperatures. The dark shading symbolizes electrons.



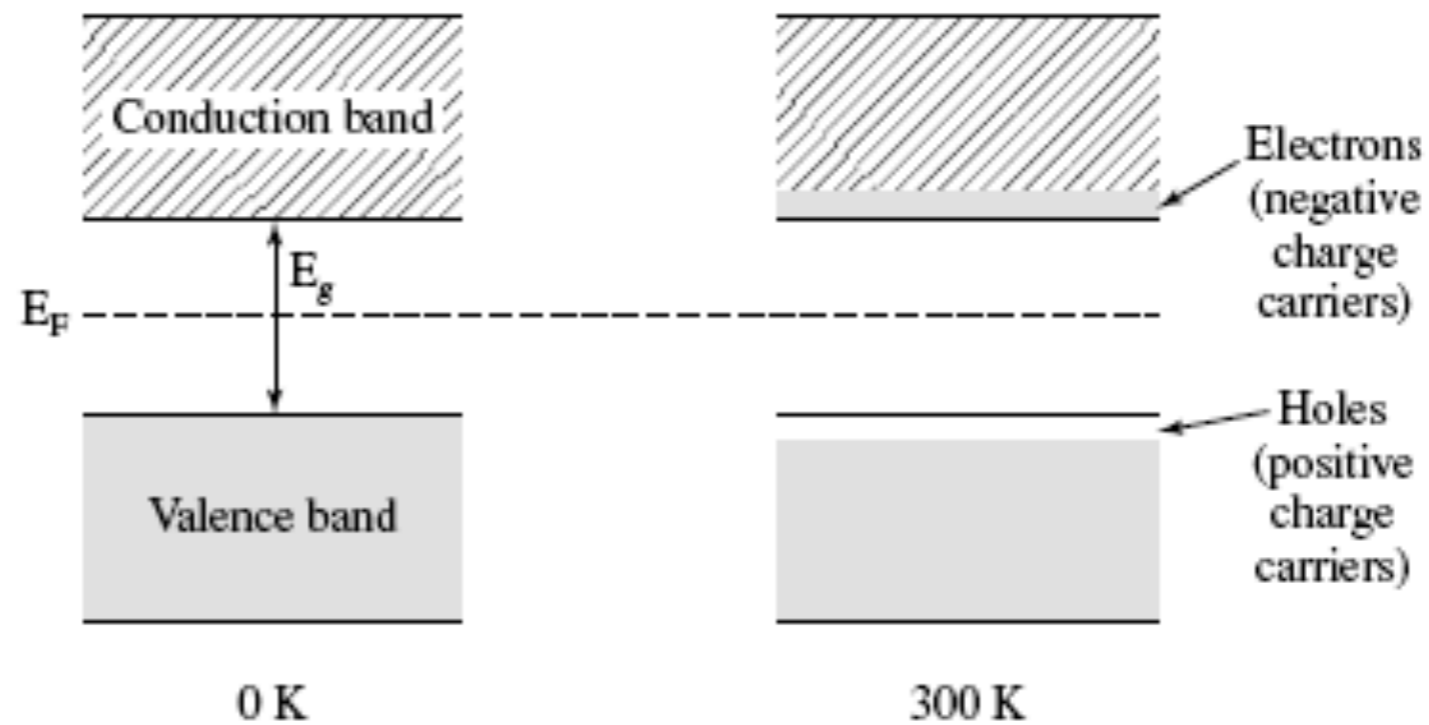
$$N_e = 4.84 \times 10^{15} T^{3/2} \exp \left[- \left(\frac{E_g}{2k_B T} \right) \right],$$

Number of Electrons in the Conduction Band

$$\sigma = N_e \cdot \mu \cdot e,$$

Semiconductors

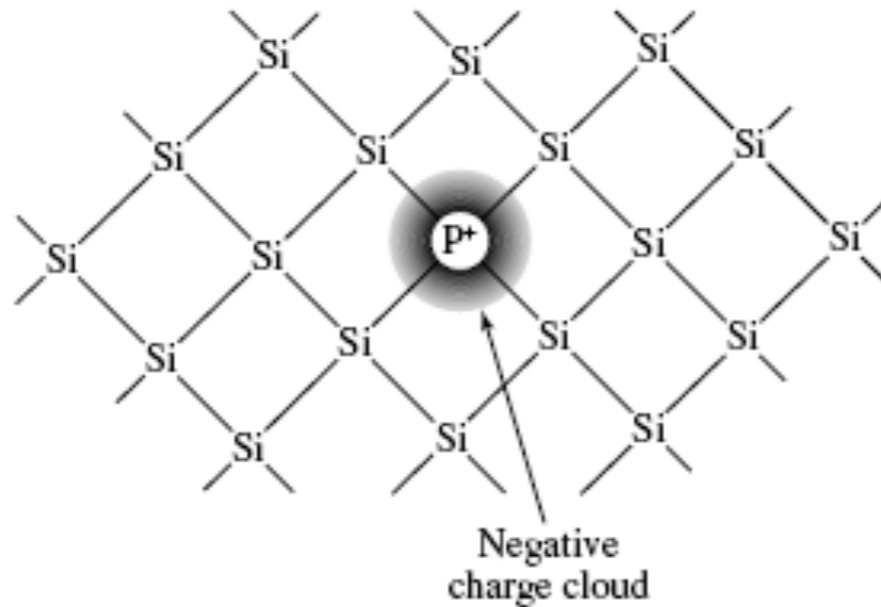
FIGURE 11.11. Simplified band diagrams for an intrinsic semiconductor such as pure silicon at two different temperatures. The dark shading symbolizes electrons.



$$\sigma = N_e \mu_e e + N_h \mu_h e,$$

Holes left in the valence band are positive charge carriers
Intrinsic Conduction in an Intrinsic Semiconductor

n-Type Semiconductors



0.0001 % P

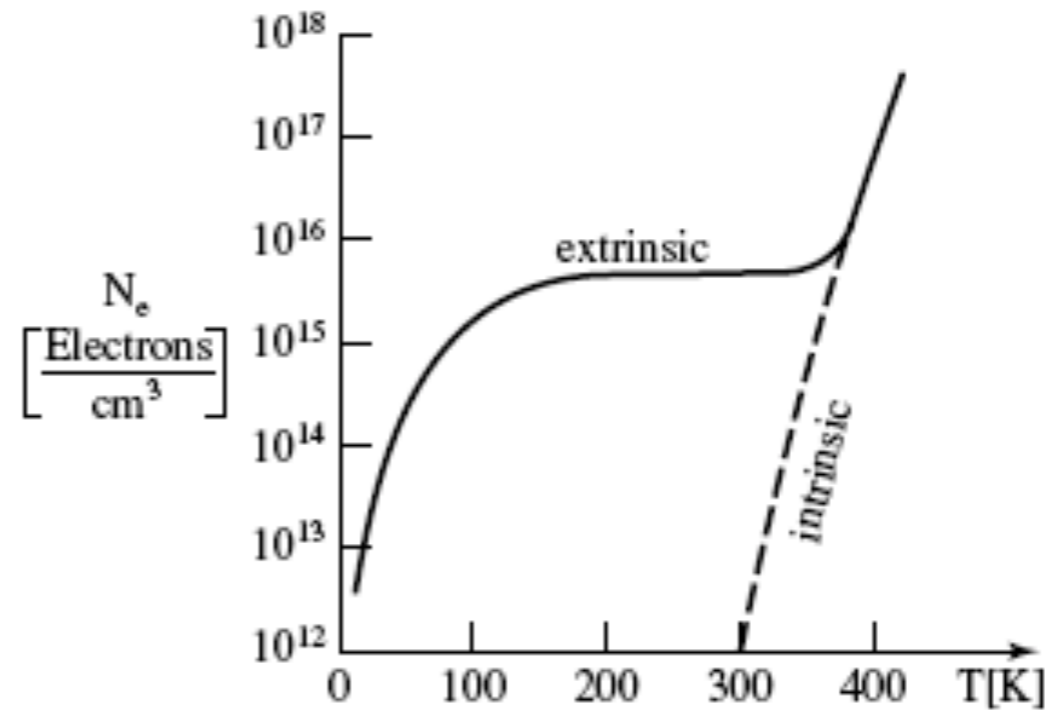
FIGURE 11.12. Two-dimensional representation of a silicon lattice in which a phosphorous atom substitutes a regular lattice atom, and thus introduces a negative charge cloud about the phosphorous atom. Each electron pair between two silicon atoms constitutes a covalent bond [see Chapter 3, particularly Figure 3.4(a)].

Silicon has 4 valence electrons, Group V elements have 5

For Phosphorous the binding energy for the donor electron is
0.045 eV (small/weakly bound)

n-Type Semiconductors

FIGURE 11.13. Schematic representation of the number of electrons per cubic centimeter in the conduction band as a function of temperature for extrinsic semiconductors, assuming low doping.



Extra conducting electrons contributed by P

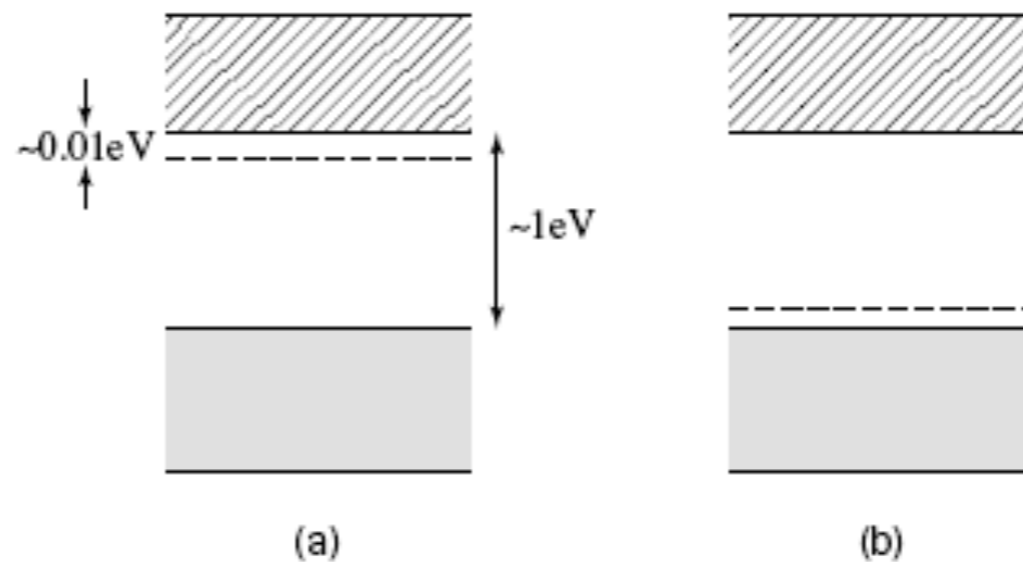


FIGURE 11.14. (a) Donor and (b) acceptor levels in extrinsic semiconductors.

p-Type Semiconductors

Group III impurities (B, Al, Ga, In) are deficient in one electron

Acceptor Impurities

Positive Charge Carriers (Holes) in the valence band

$$\sigma = N_{de} e \mu_e,$$

At room temperature only the majority carriers need be considered
(intrinsic effects are ignored)

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	Lu 71	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Lr 103	Db 104	Jl 105	Rf 106	Bh 107	Hn 108	Mt 109									

Compound Semiconductors

III & V

GaAs

II & VI

ZnO

ZnS

ZnSe

CdTe

For LED's
Solar Cells

La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70
Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102

Hall Effect

Are the Charge Carriers Positive or Negative?

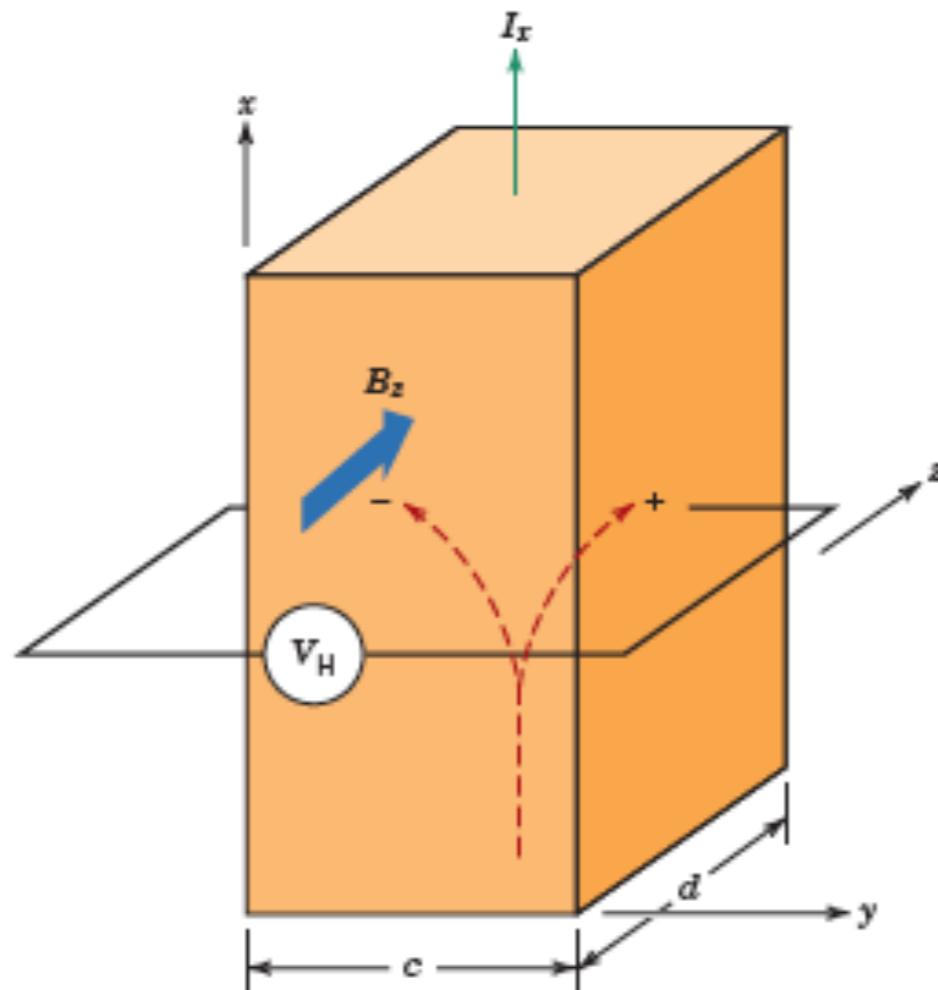


Figure 18.20 Schematic demonstration of the Hall effect. Positive and/or negative charge carriers that are part of the I_x current are deflected by the magnetic field B_z and give rise to the Hall voltage, V_H .

$$V_H = \frac{R_H I_x B_z}{d}$$

$$R_H = \frac{1}{n|e|}$$

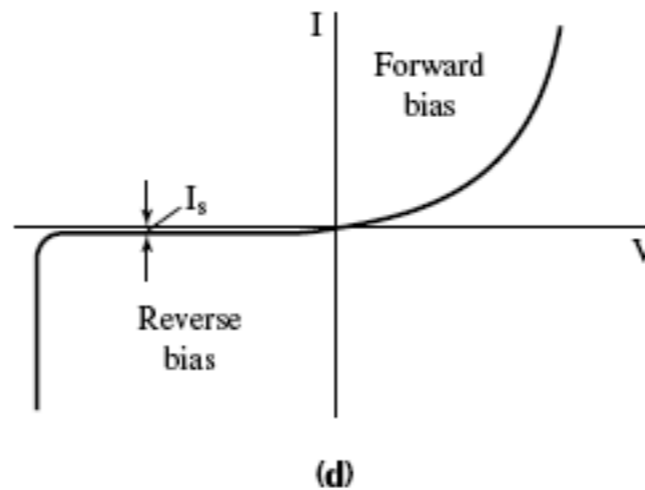
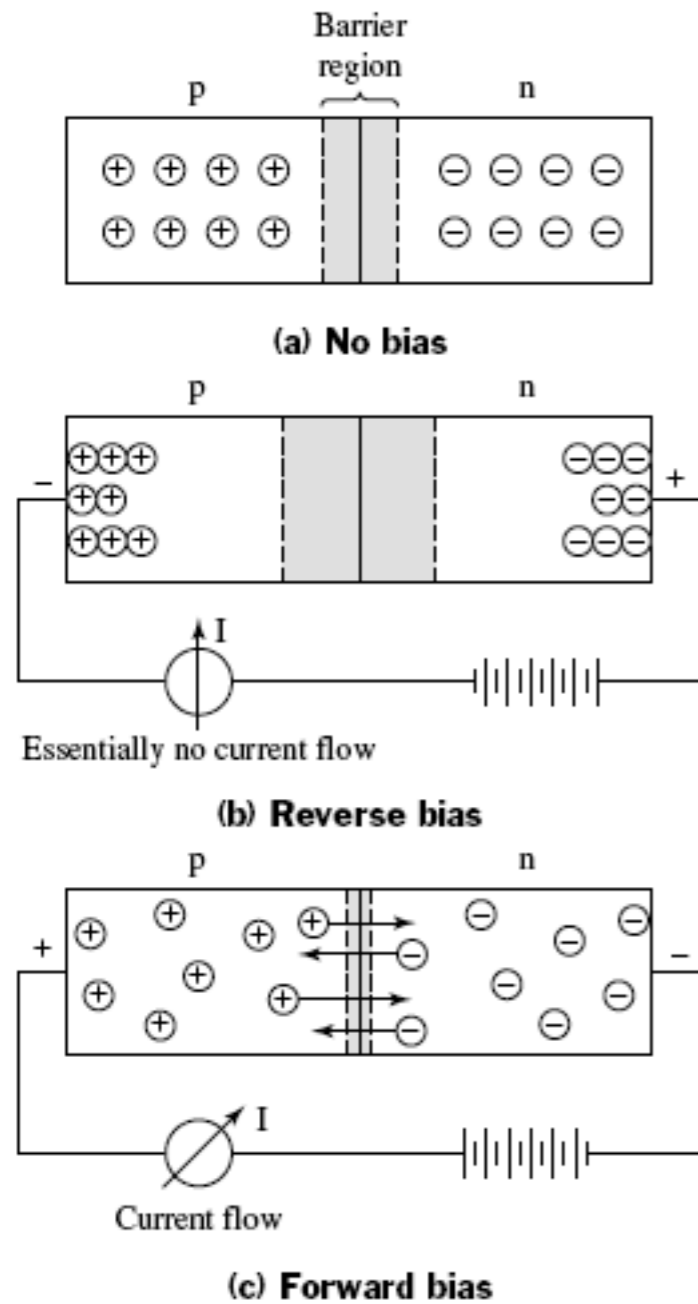
Metals Negative

$$\mu_e = \frac{\sigma}{n|e|}$$

$$\mu_e = |R_H| \sigma$$

R_H = Hall Coefficient

Rectifier or Diode



$$I = I_s \left[\exp\left(\frac{eV}{k_B T}\right) - 1 \right],$$

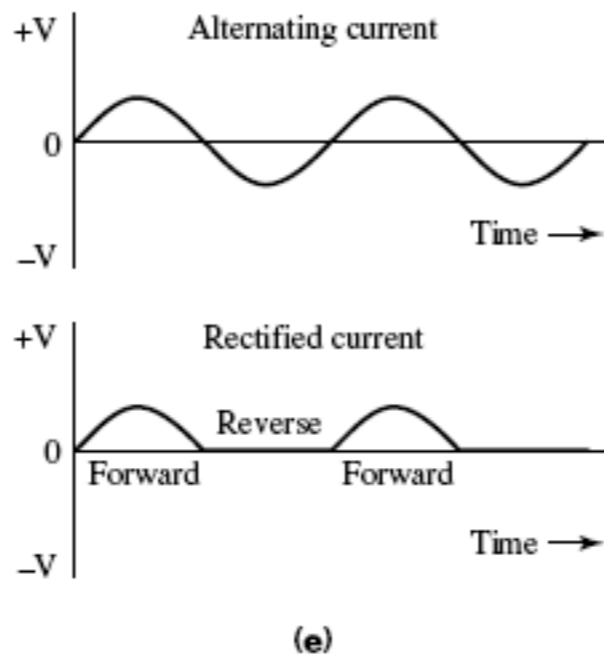


FIGURE 11.15. Schematic representation of (a) an unbiased p-n junction, (b) a p-n junction in reverse bias, (c) a p-n junction in forward bias, (d) current-voltage characteristics of a p-n rectifier, and (e) voltage versus time curves.

Rectifier or Diode

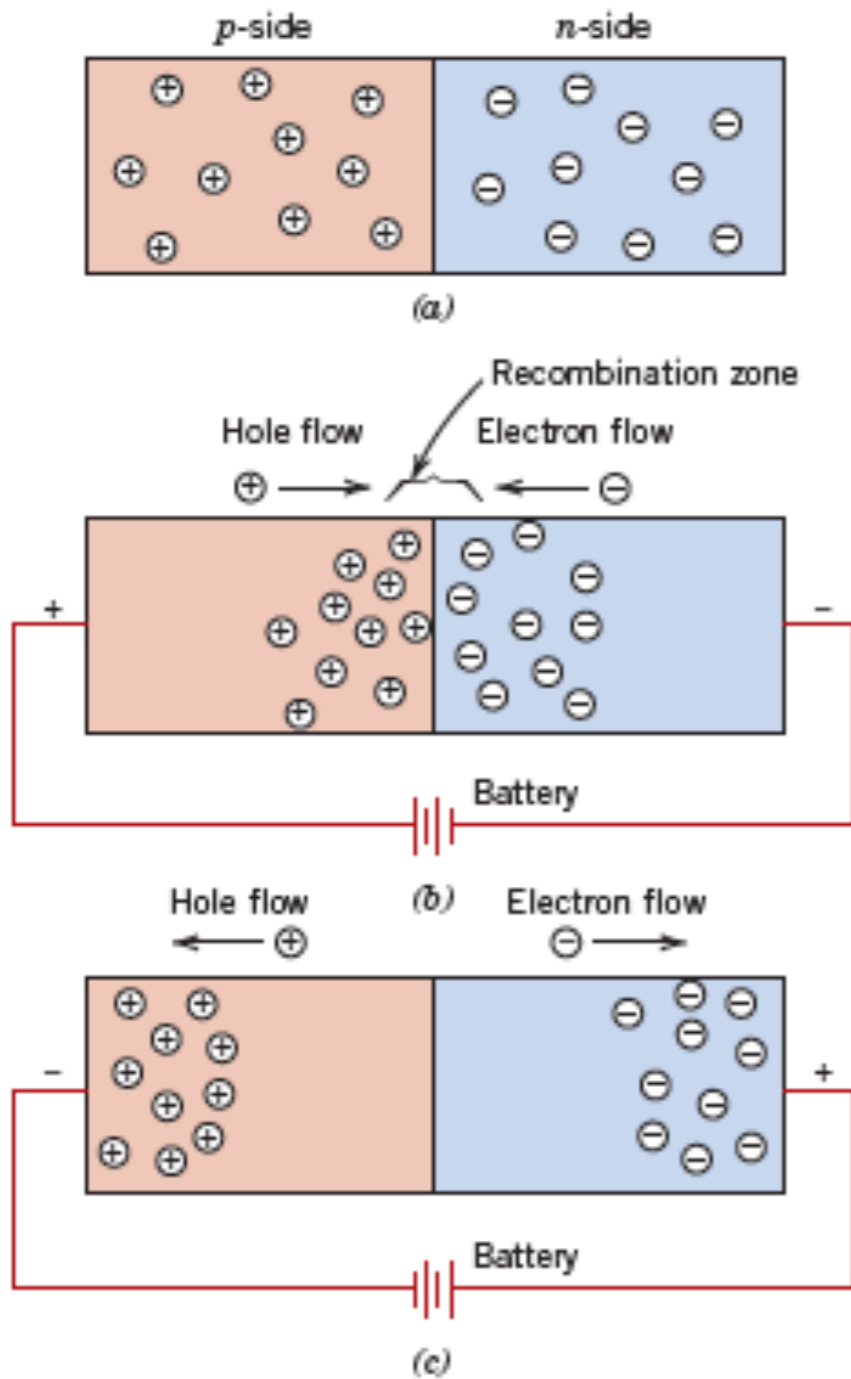


Figure 18.21 For a p - n rectifying junction, representations of electron and hole distributions for (a) no electrical potential, (b) forward bias, and (c) reverse bias.

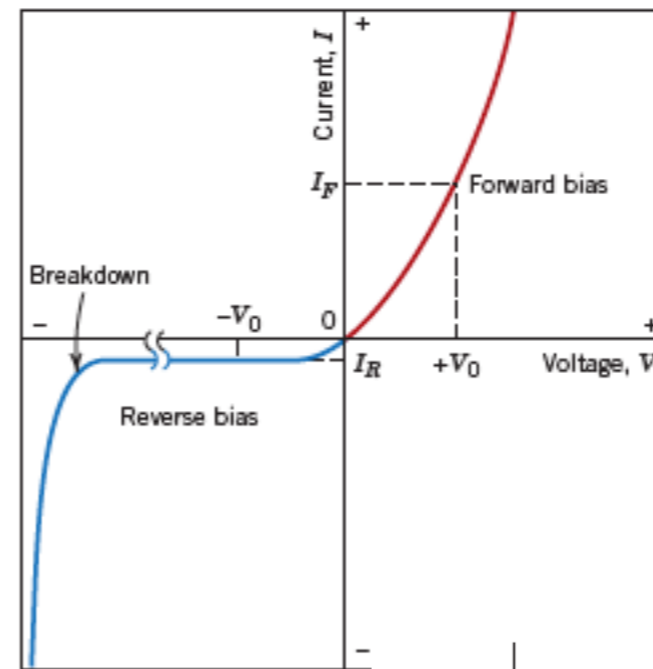


Figure 18.22 The current-voltage characteristics of a p - n junction for forward and reverse biases. The phenomenon of breakdown is also shown.

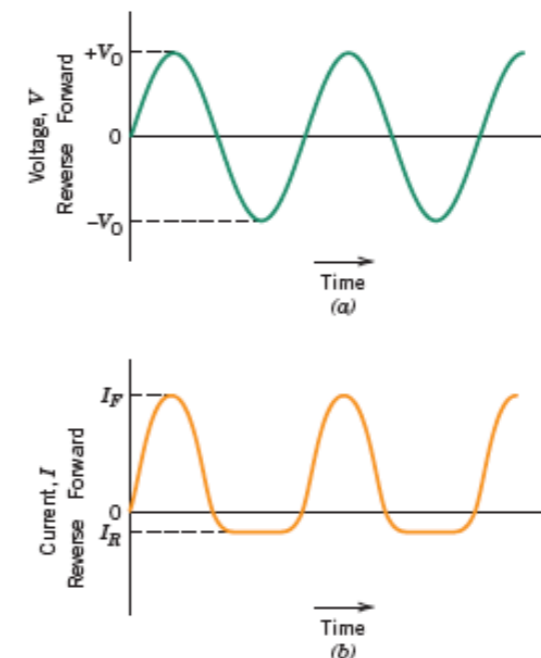


Figure 18.23 (a) Voltage versus time for the input to a p - n rectifying junction. (b) Current versus time, showing rectification of voltage in (a) by a p - n rectifying junction having the voltage-current characteristics shown in Figure 18.22.

Rectifier or Diode

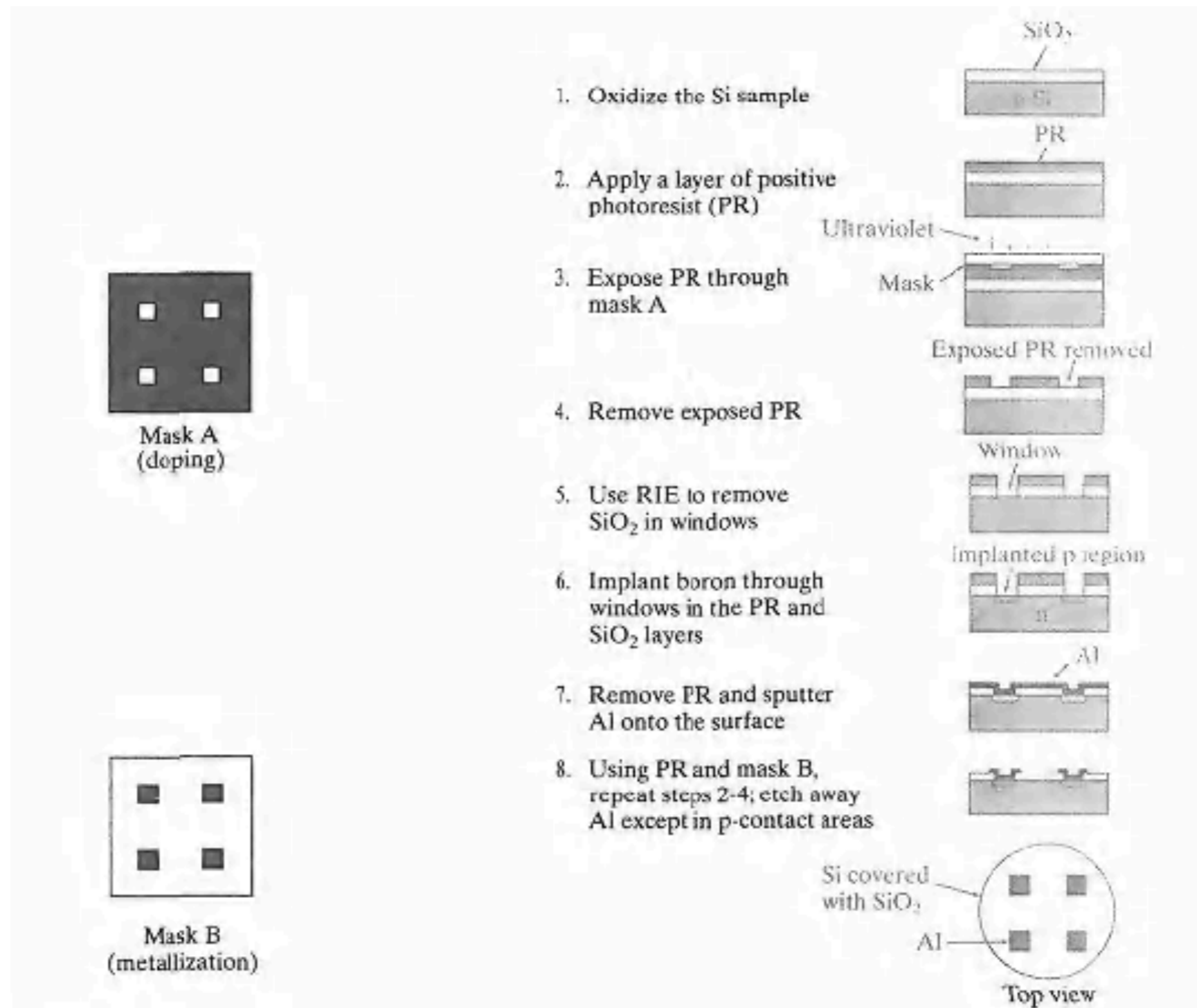


Figure 5-10
Simplified description of steps in the fabrication of p-n junctions. For simplicity, only four diodes per wafer are shown, and the relative thicknesses of the oxide, PR, and the Al layers are exaggerated.

Rectifier or Diode

On contact a potential is setup between p and n materials due to flow of electrons from n to p and holes from p to n

This barrier potential opposes flow of electrons. If electrons are added to the p side the potential barrier drops (Forward Bias).

If electrons are added to n the potential barrier increases (Reverse Bias).

So current can only flow from p to n under normal circumstances.

A slight time lag occurs due to motion of minority carriers in a p-n junction and there is energy loss due to this motion.

Rectifier or Diode

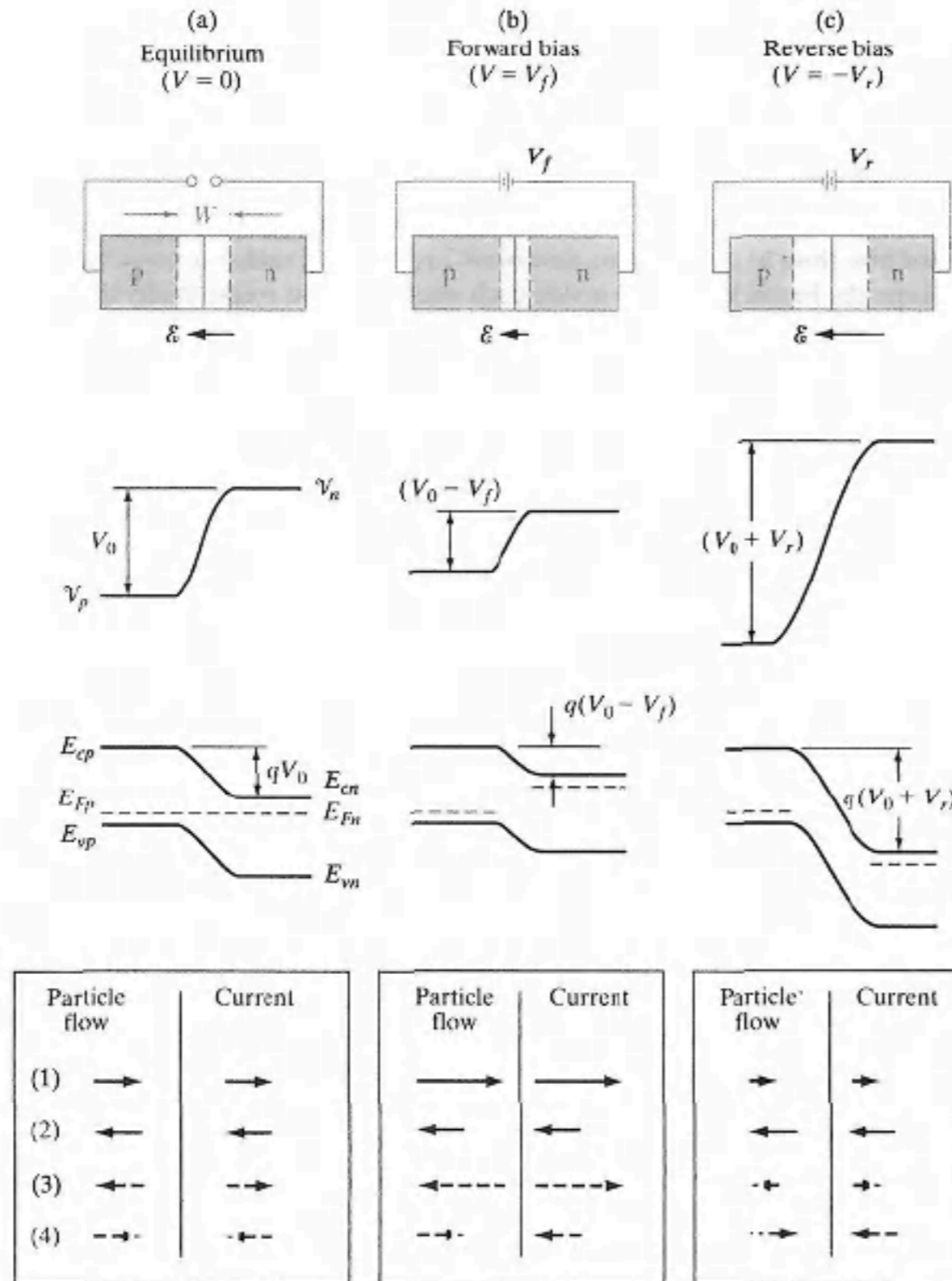


Figure 5-13
Effects of a bias at a p-n junction; transition region width and electric field, electrostatic potential, energy band diagram, and particle flow and current directions within W for (a) equilibrium, (b) forward bias, and (c) reverse bias.

(1) Hole diffusion
(2) Hole drift

(3) Electron diffusion
(4) Electron drift

Rectifier or Diode

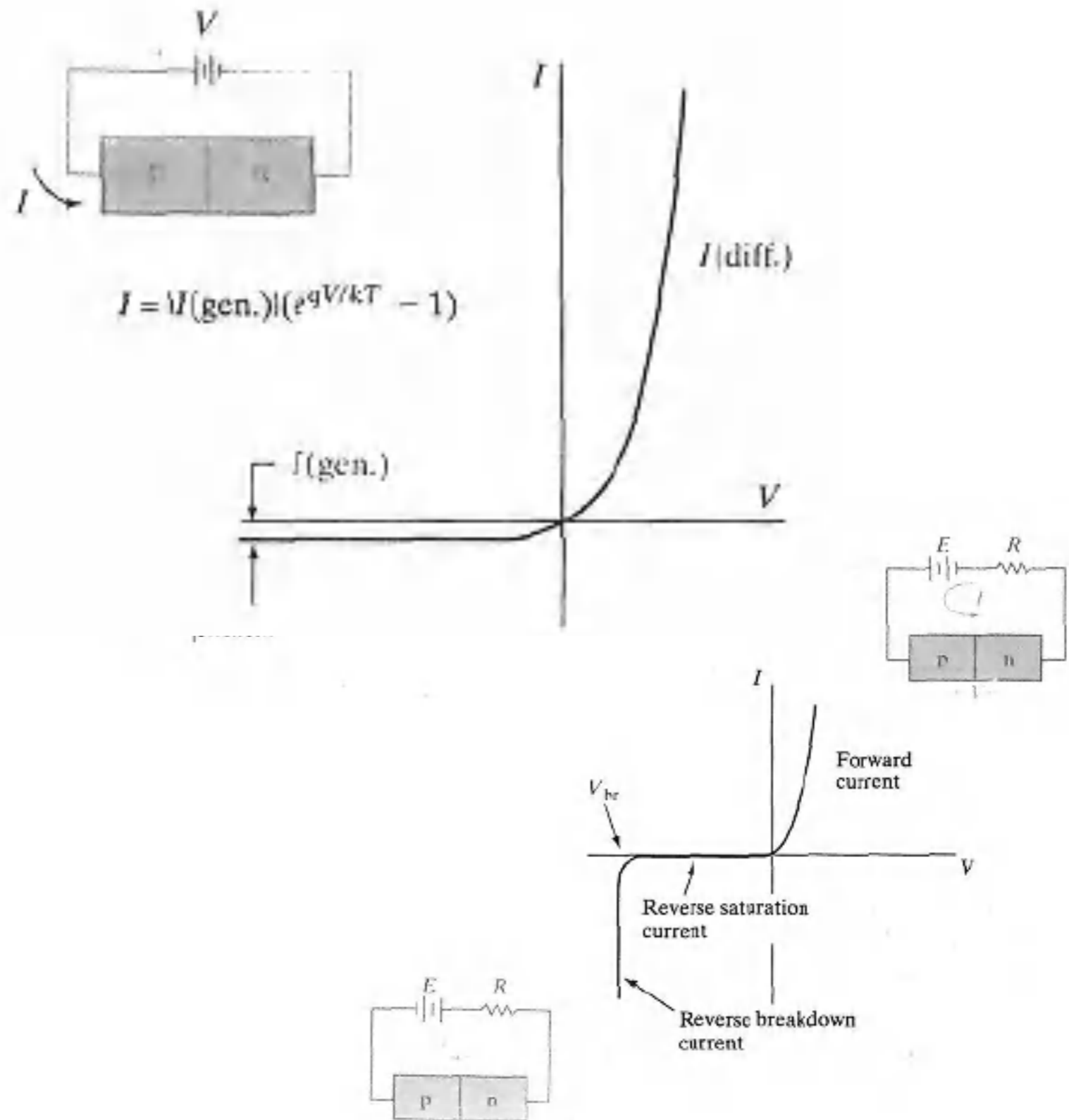
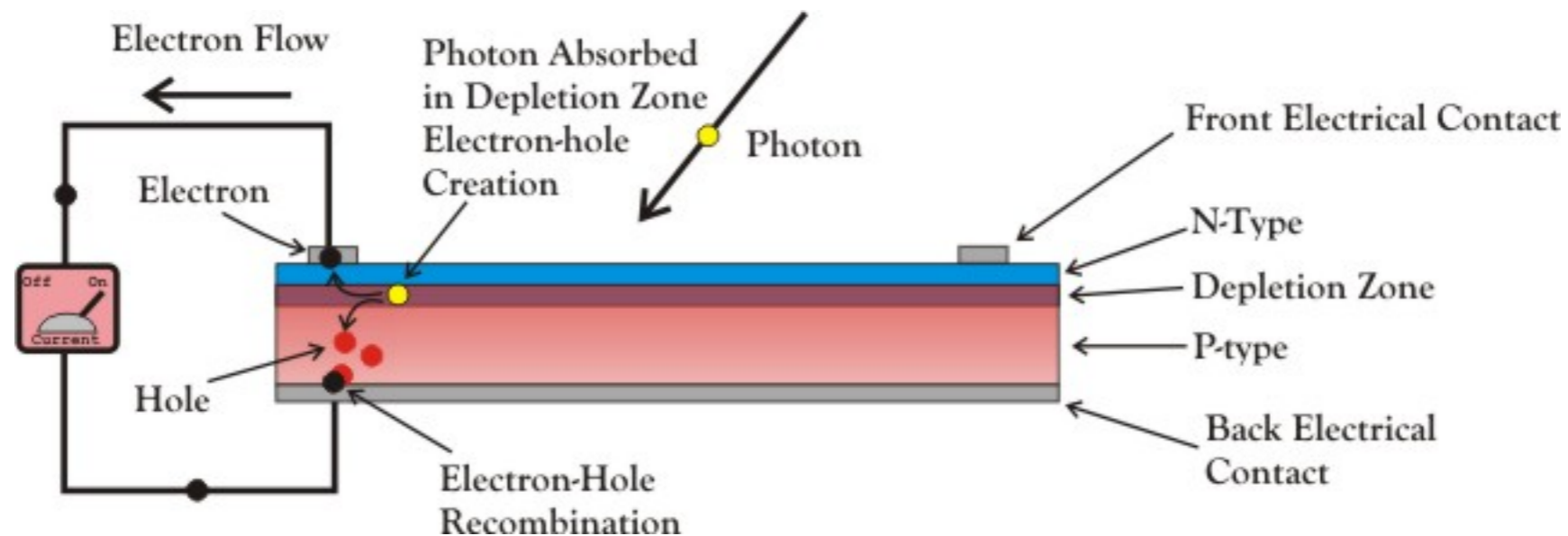
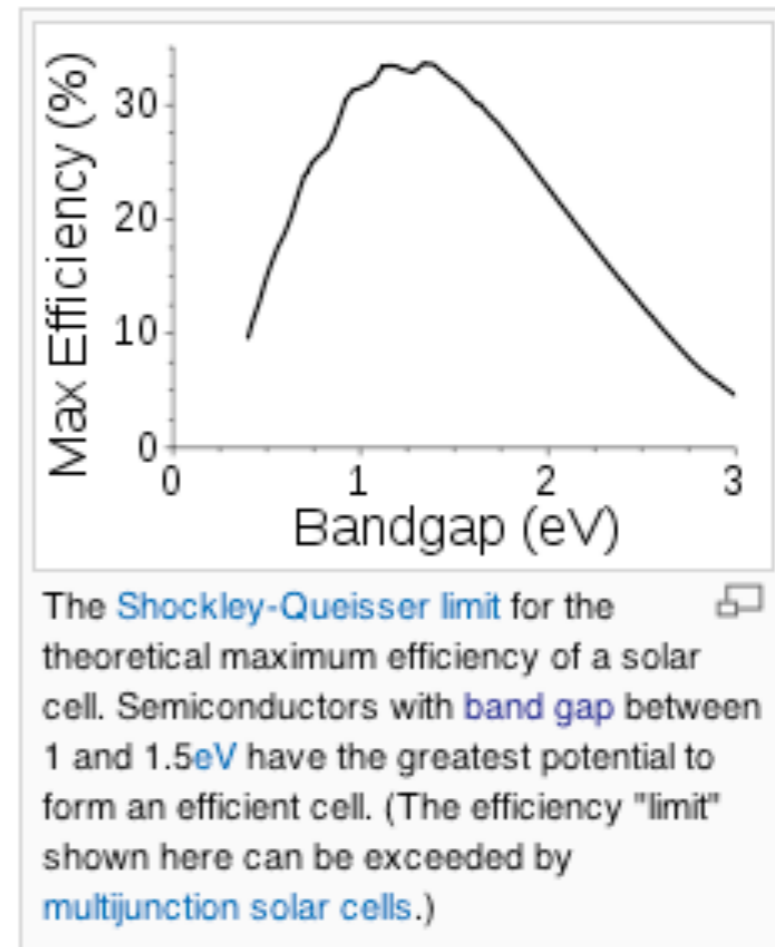
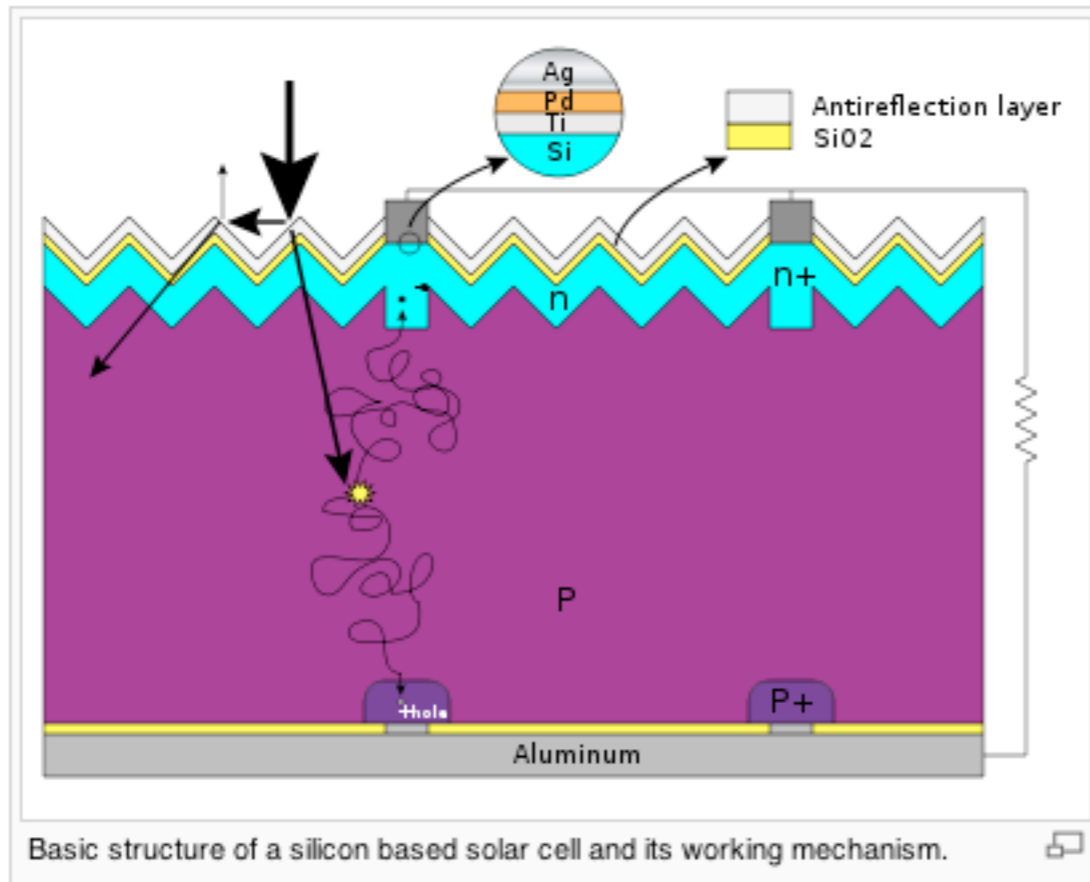


Figure 5-14
I-V characteristic
of a p-n junction.

Solar Cell



Solar Cell

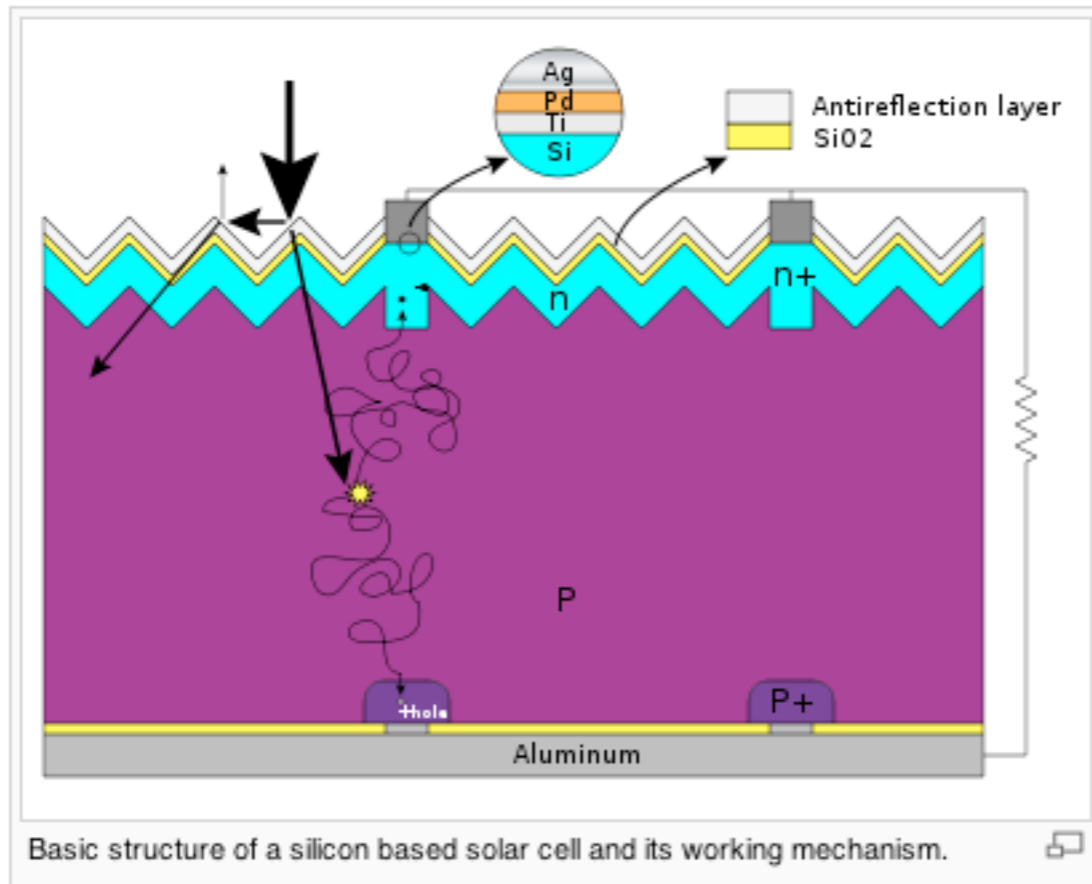
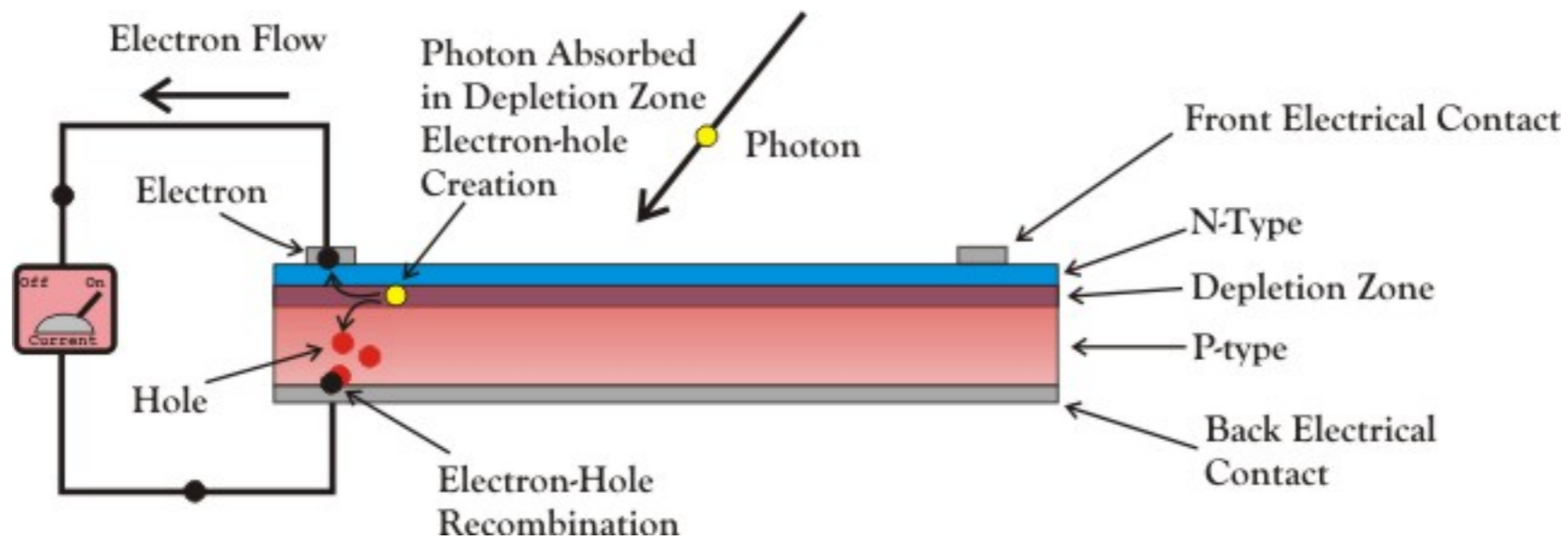
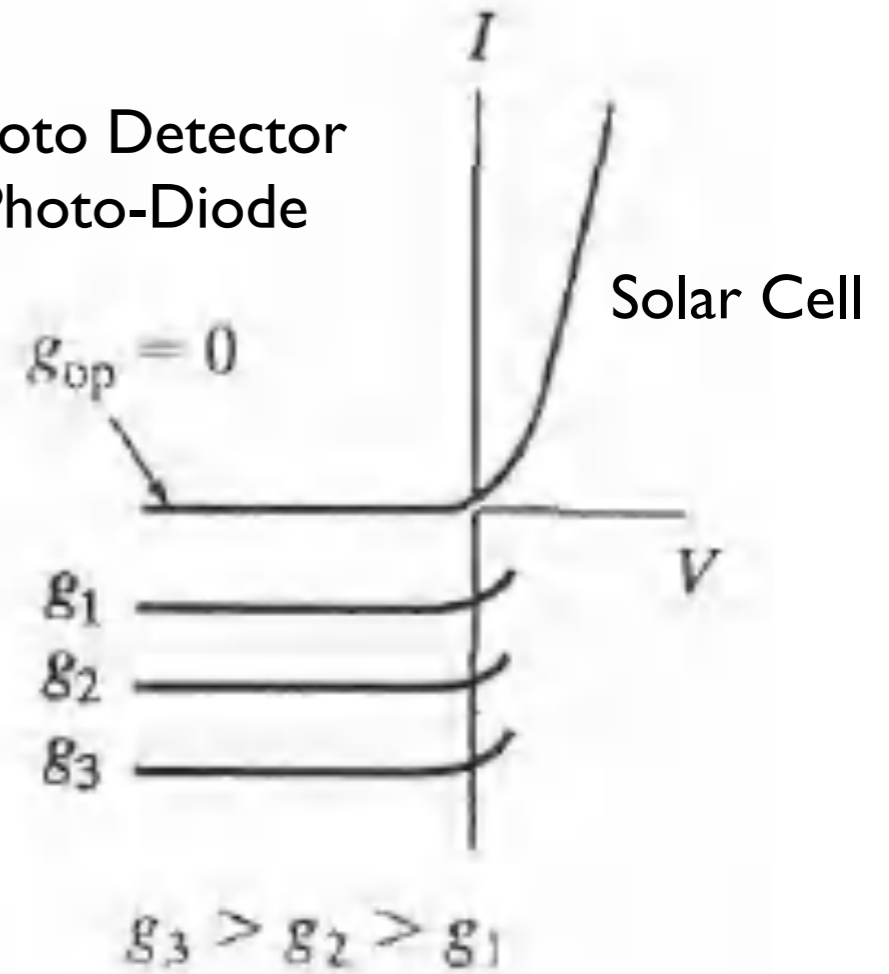


Photo Detector
Photo-Diode



Solar Cell

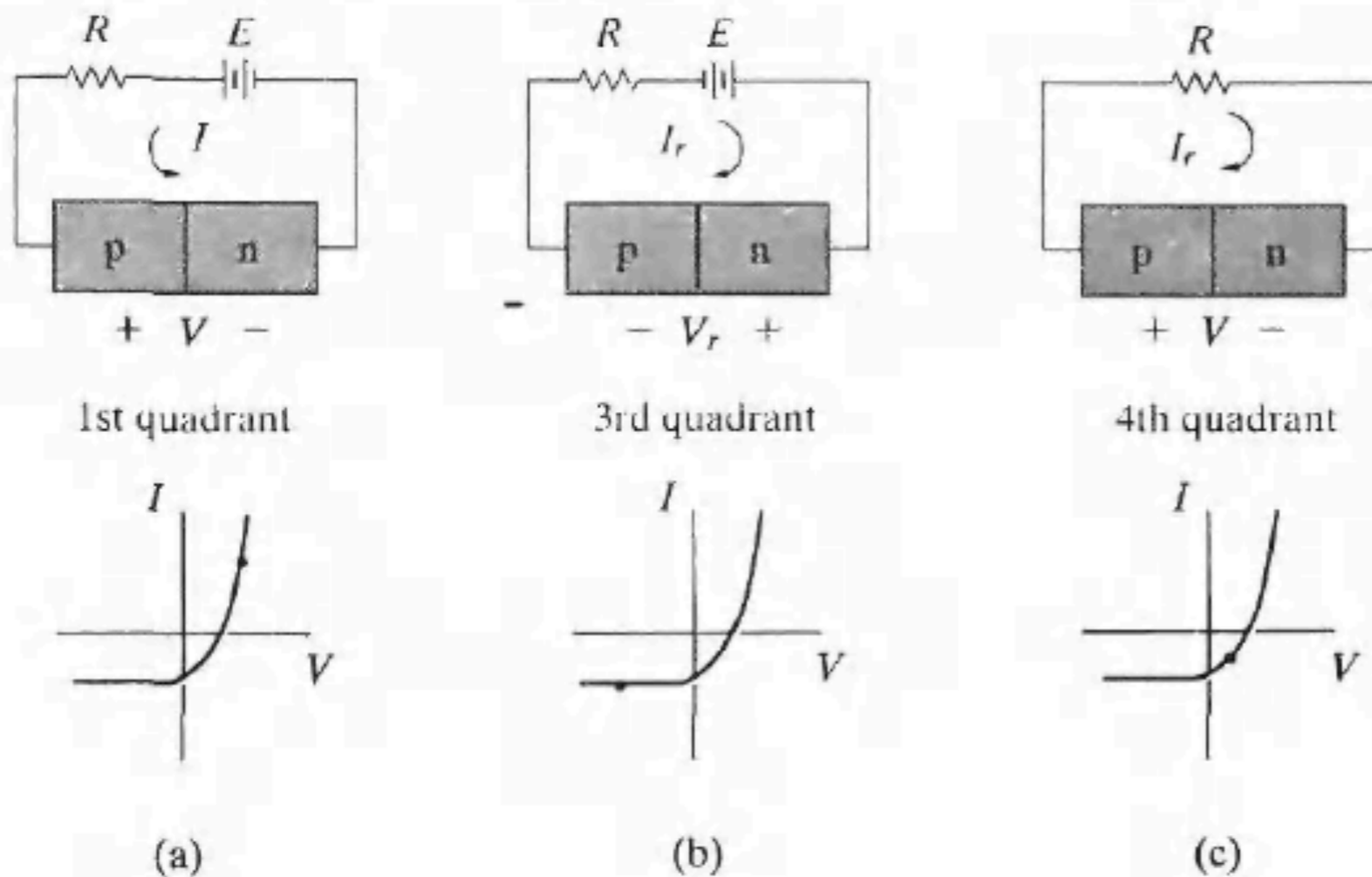
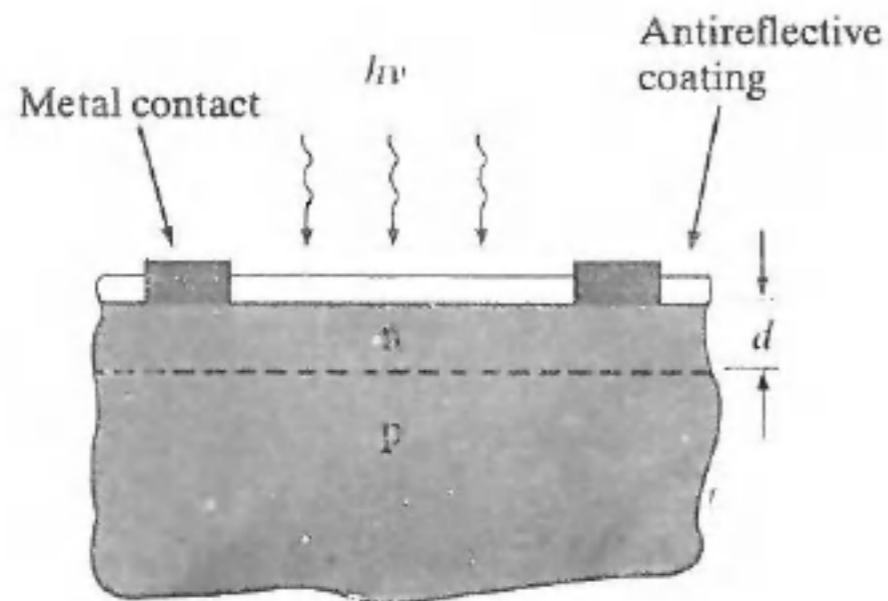
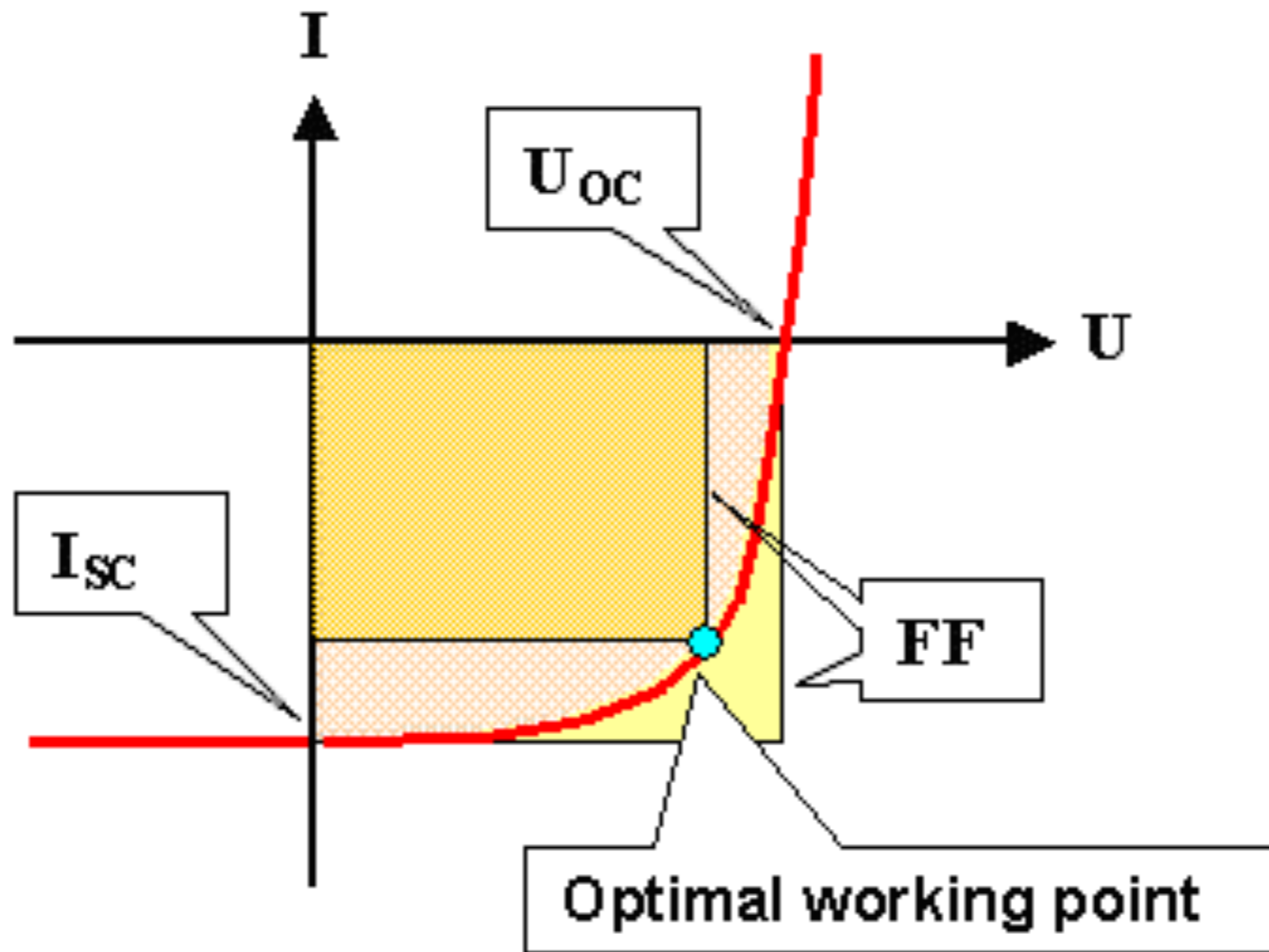


Figure 8-3

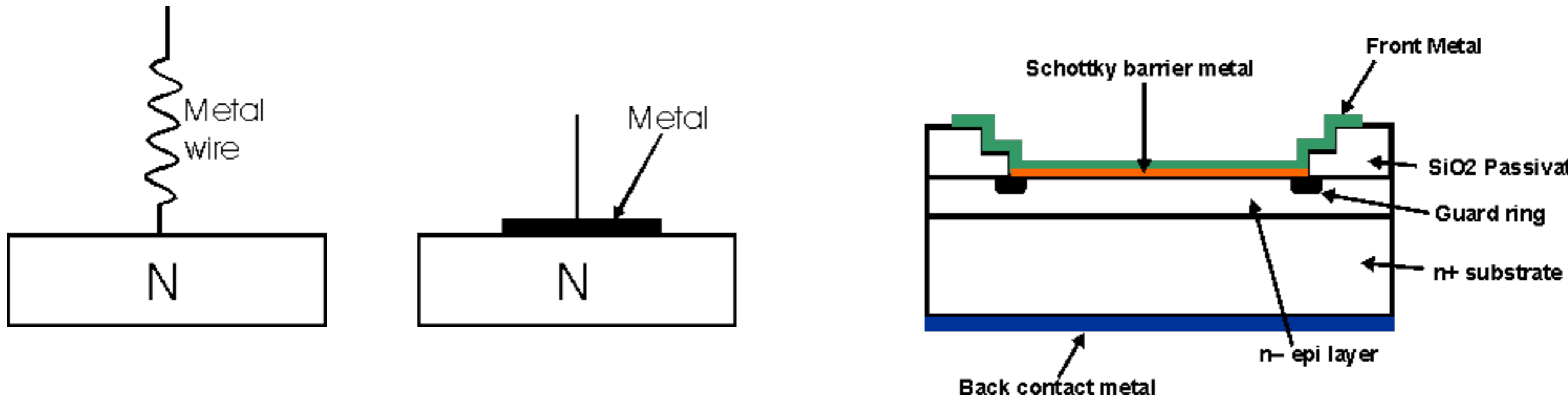
Operation of an illuminated junction in the various quadrants of its $I-V$ characteristic; in (a) and (b), power is delivered to the device by the external circuit; in (c) the device delivers power to the load.



Solar Cell



Schottky Diode



Work Function of a metal in vacuum

Energy $q\Phi_m$ is required to remove an electron at the Fermi level to the vacuum

4.3 V for Al, 4.8 V for Au

if negative charges (n-Si) is brought near the metal surface the work function is reduced due to induced positive charges: Schottky Effect.

Semi-conductor work function $q\Phi_s$

Charge transfer leads to adjustment of Fermi levels

A positive depletion layer occurs in the semiconductor if the metal work function is larger than the semiconductor work function.

Schottky Diode

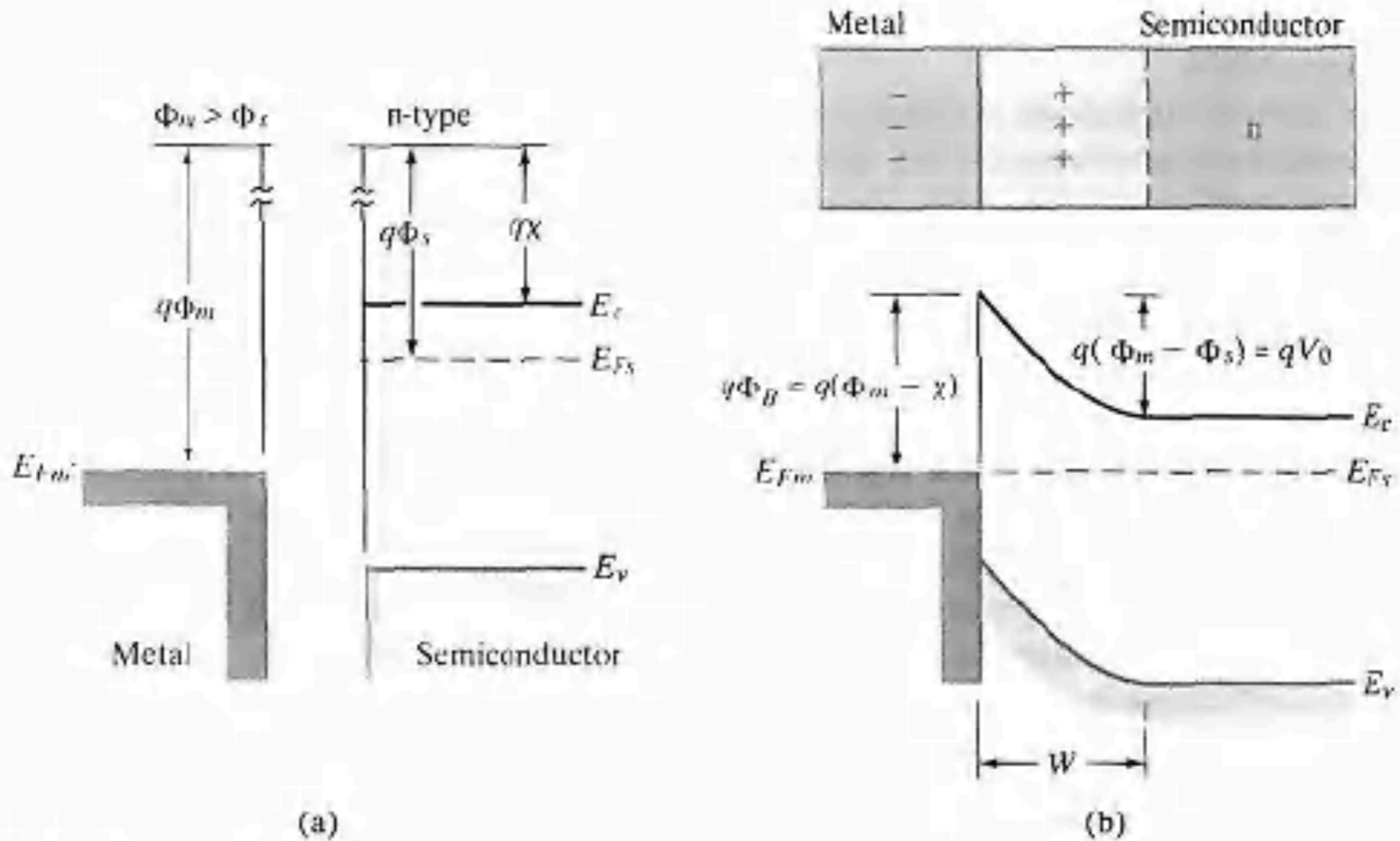
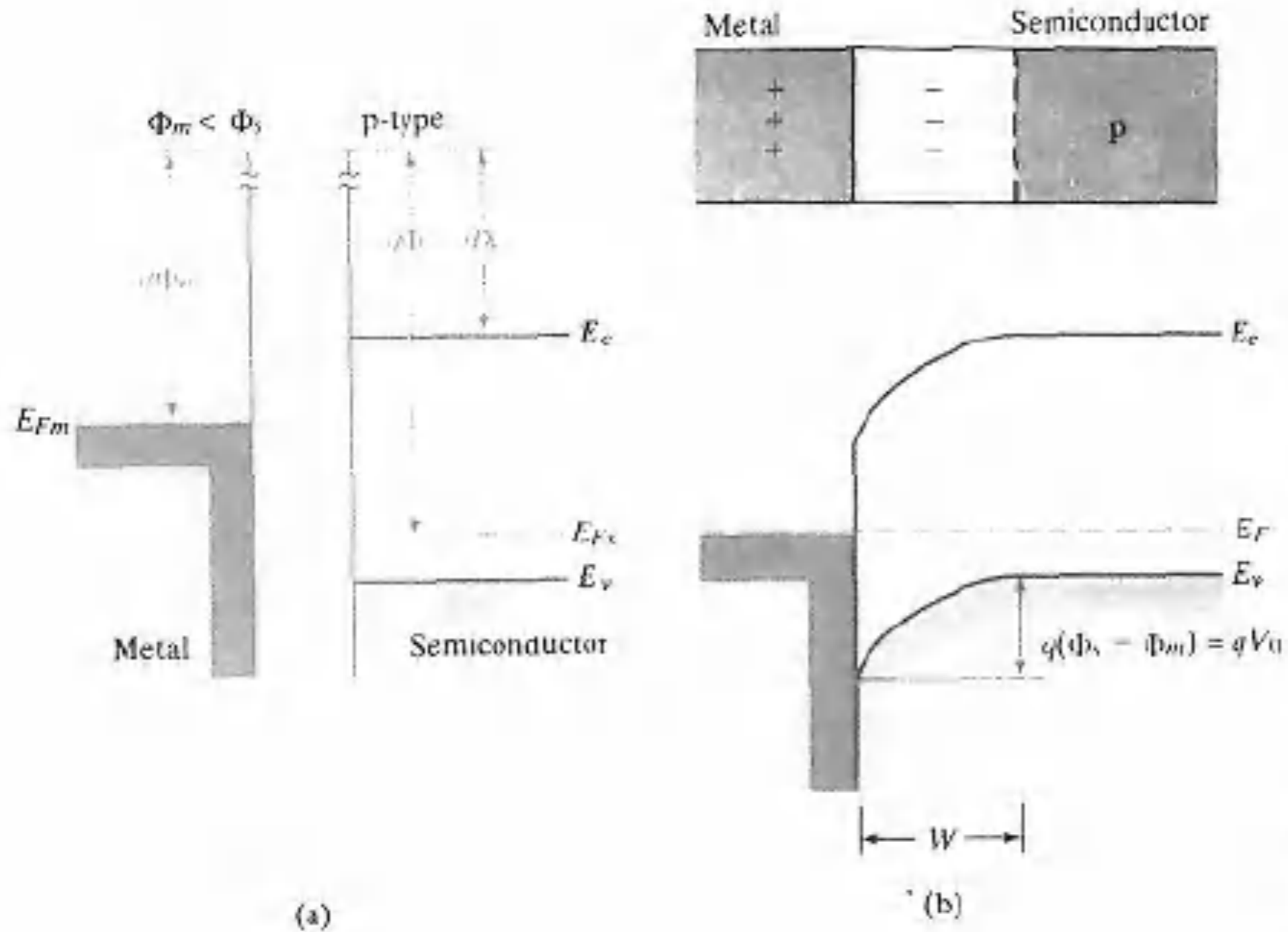


Figure 5-40
 A Schottky barrier formed by contacting an n-type semiconductor with a metal having a larger work function: (a) band diagrams for the metal and the semiconductor before joining; (b) equilibrium band diagram for the junction.

Schottky Diode



Metal work function is less than p-semiconductor for a p-type

Ohmic Contact

For an n-type semiconductor if $\Phi_m < \Phi_s$ the electrons (majority carriers) from the metal flow to the semiconductor

For a p-type semiconductor if $\Phi_m > \Phi_s$ the electrons from the semiconductor flow to the metal

So Ohmic contacts, needed for normal electrical connections, involve the opposite condition as a Schottky contact

Hetero-Junctions

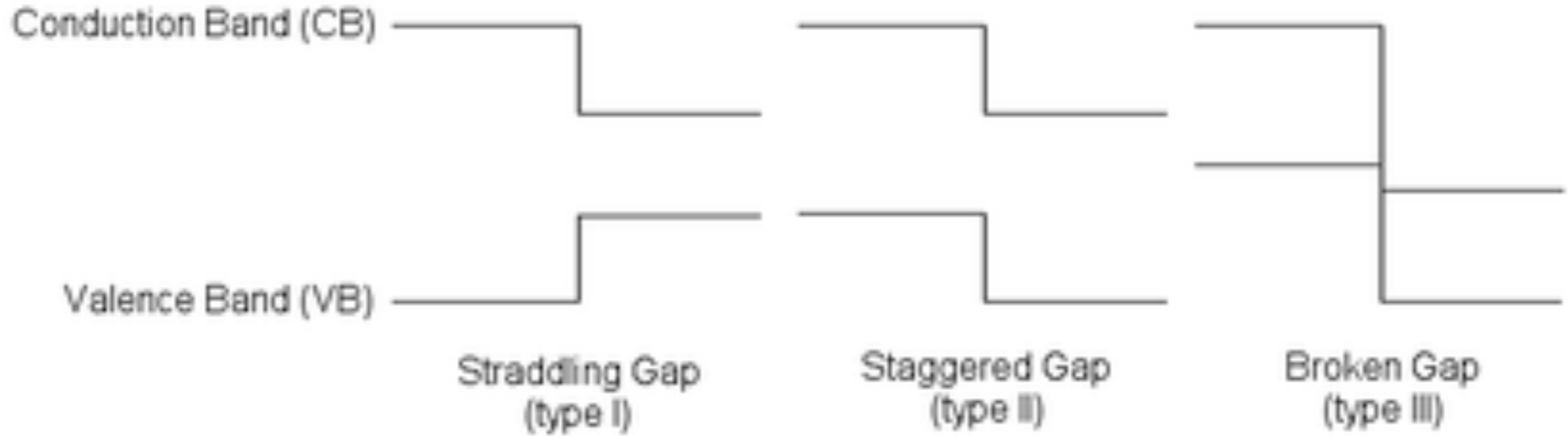
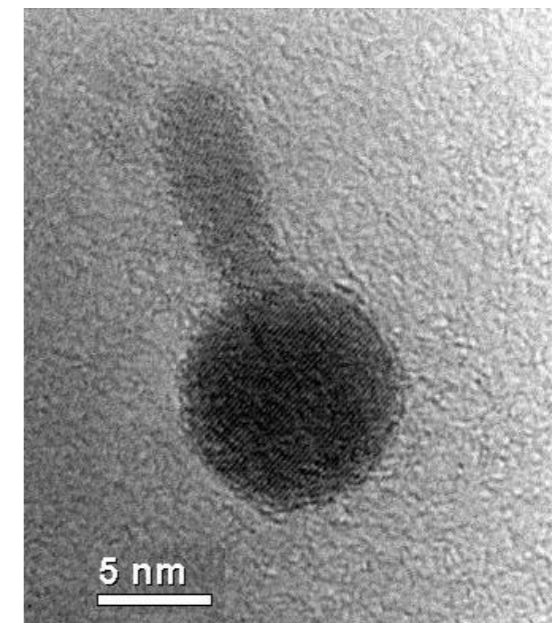


Image of a nanoscale heterojunction between iron oxide (Fe_3O_4 — sphere) and cadmium sulfide (CdS — rod) taken with a [TEM](#). This staggered gap (type II) offset junction was synthesized by Hunter McDaniel and Dr. Moonsub Shim at the University of Illinois in Urbana-Champaign in 2007.



Transistor

Three terminal device in which current through two terminals is controlled by a small current or voltage through the third terminal

Transistors are used for Amplification and Switching

Transistor is a control device

Bipolar Junction Transistor

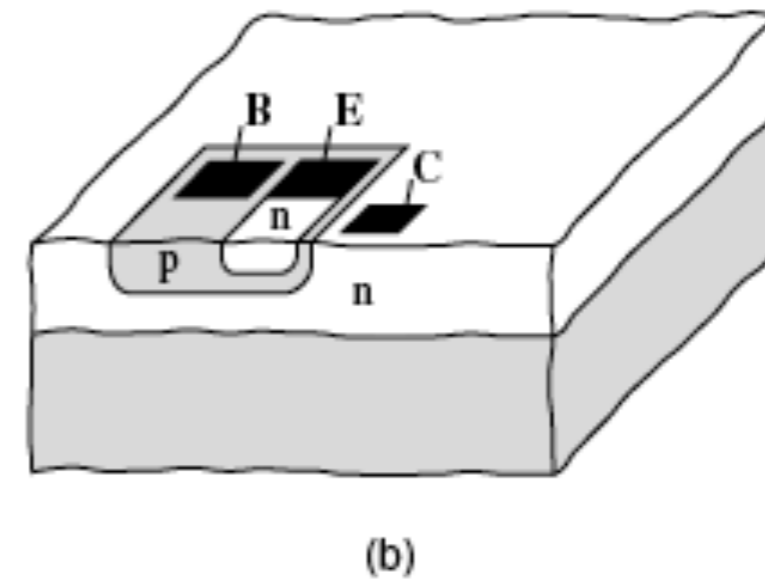
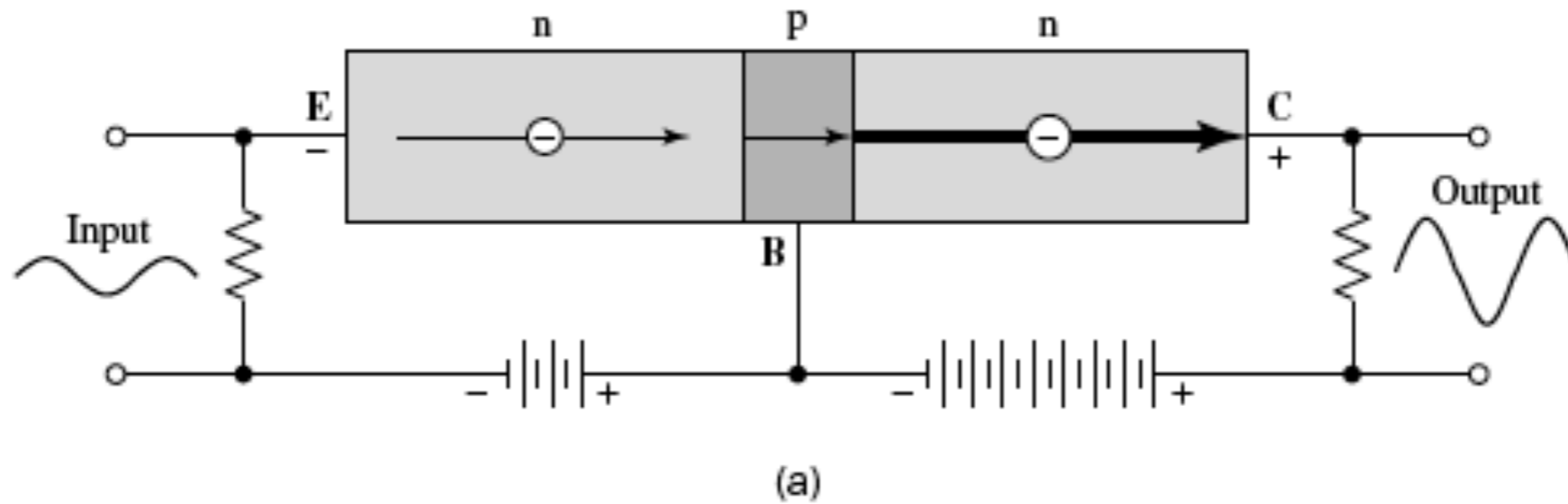


FIGURE 11.16. (a) Biasing of an n-p-n bipolar transistor. (b) Schematic representation of an n-p-n bipolar transistor. The dark areas are the contact pads.

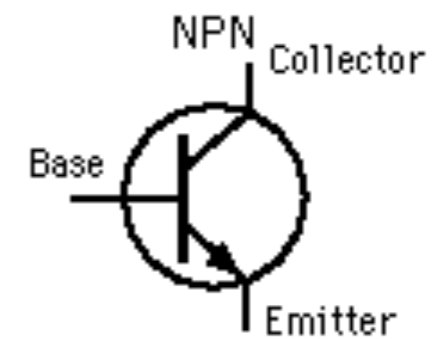
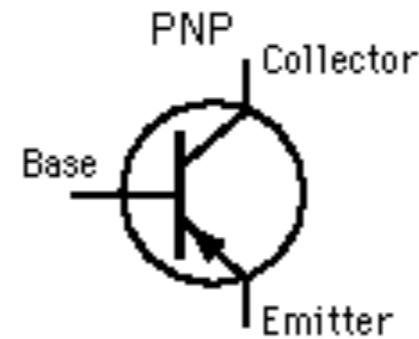
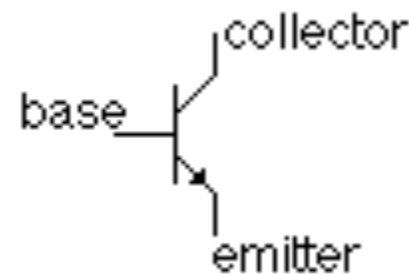
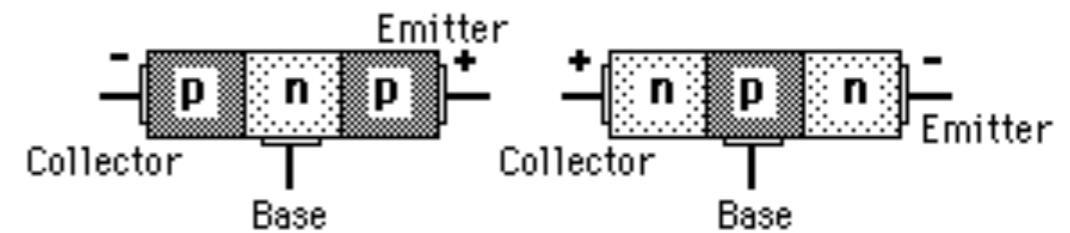
Emitter (E) Base (B) Collector (C)

Bipolar Junction Transistor

Acts like a valve. You have a gate controlled by a small voltage
That controls a large current.
It can act as an amplifier or as a switch.



Assorted discrete transistors.
Packages in order from top to bottom:
TO-3, TO-126, TO-92, SOT-23



Copyright: GSU

PNP

NPN

Number of holes in base control flow

Emitter more positive than the Base
Base more positive than Collector

Base more positive than the Emitter
Collector more positive than Base

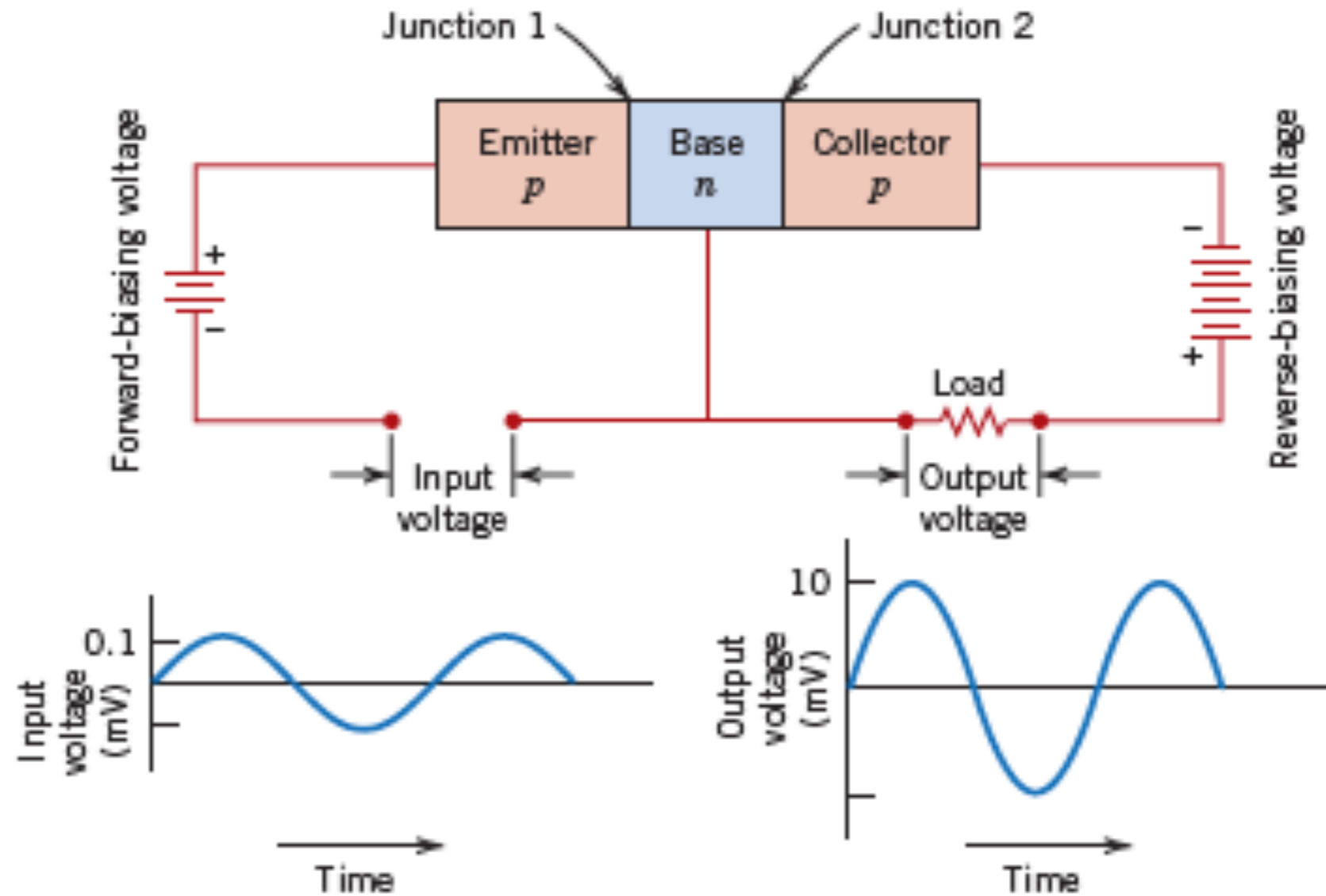
Number of electrons in base control flow

Bipolar Junction Transistor

Figure 18.24

Schematic diagram of a $p-n-p$ junction transistor and its associated circuitry, including input and output voltage–time characteristics showing voltage amplification.

(Adapted from A. G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976.)



Metal Oxide Semiconductor Field Effect Transistor MOSFET

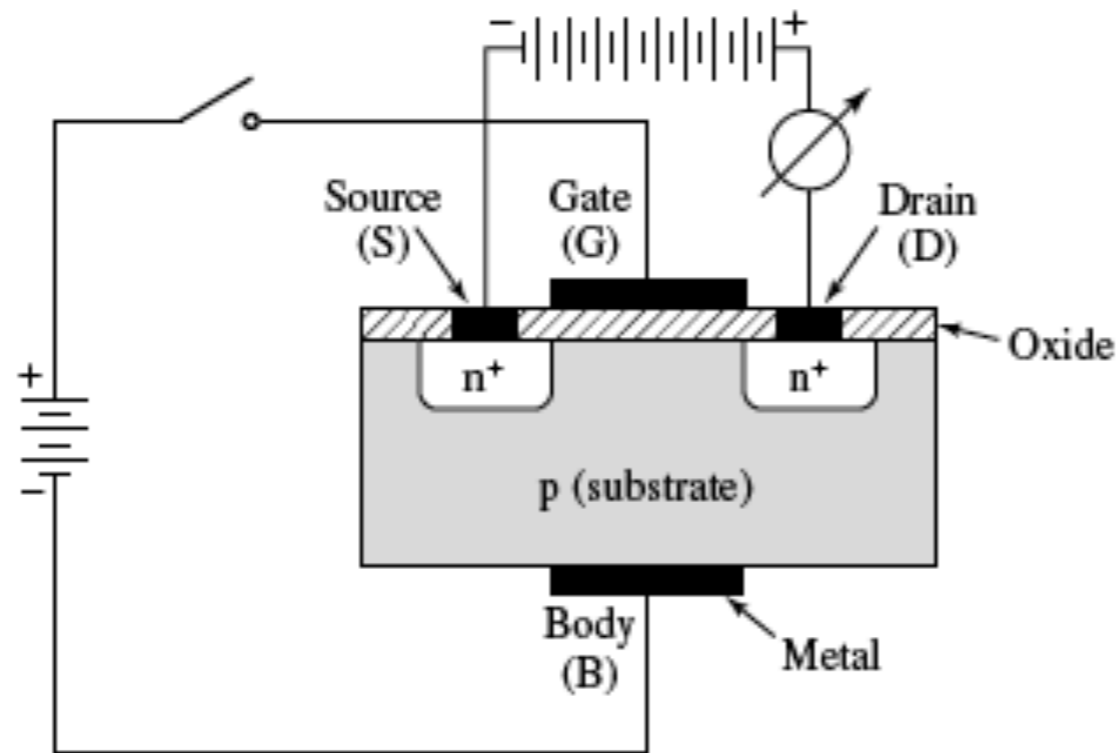
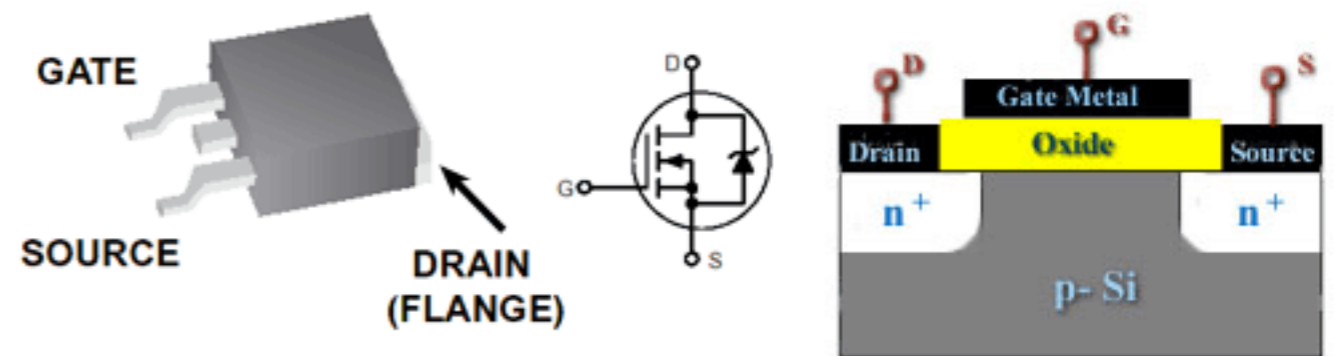
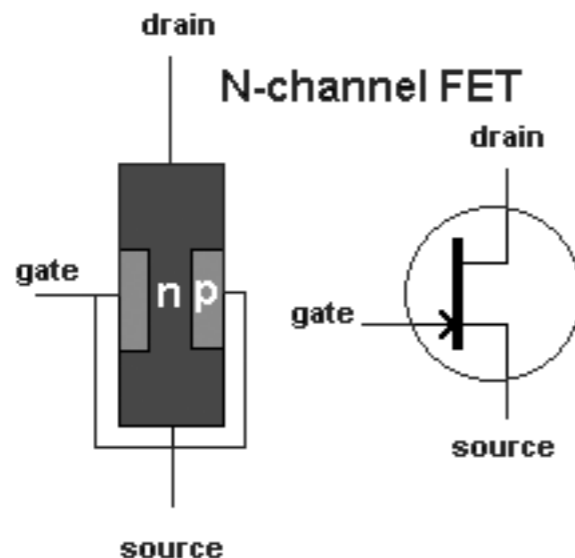
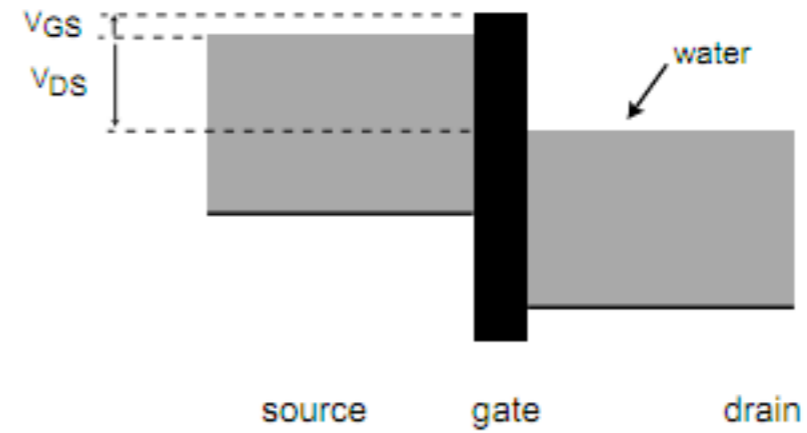
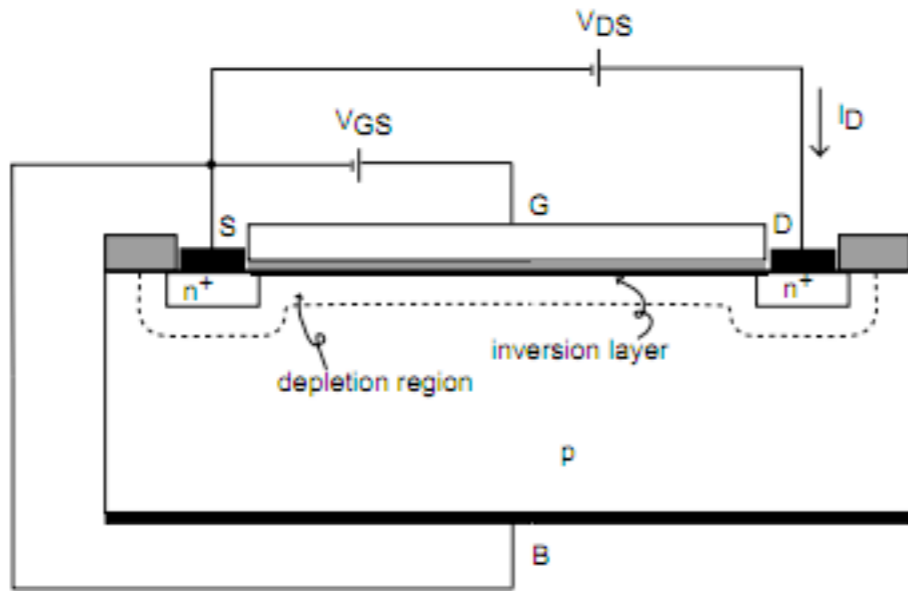


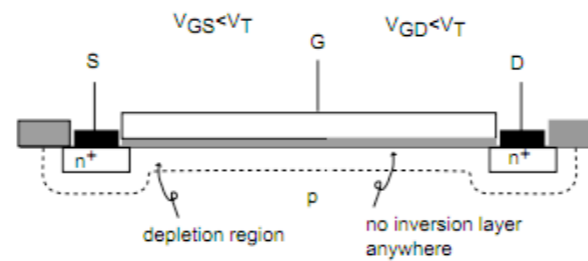
FIGURE 11.17. Normally-off-type n-channel MOSFET. The dark areas symbolize the (aluminum) metallizations. The "oxide" layer consists of SiO_2 or Si_3N_4 . This layer is about 10 nm thick. Quite often, the B and S terminals are interconnected.





□ *Cut-off regime:*

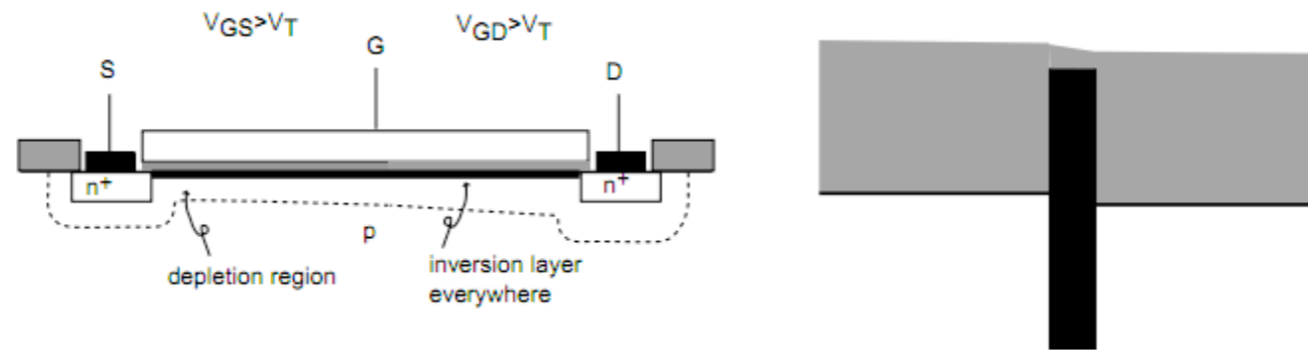
- MOSFET: $V_{GS} < V_T$, $V_{GD} < V_T$ with $V_{DS} > 0$.
- Water analogy: gate closed; no water can flow regardless of relative height of source and drain reservoirs.



$$I_D = 0$$

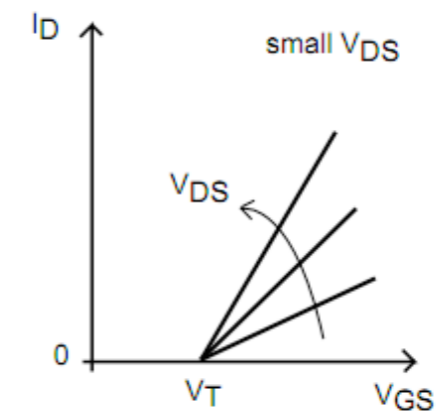
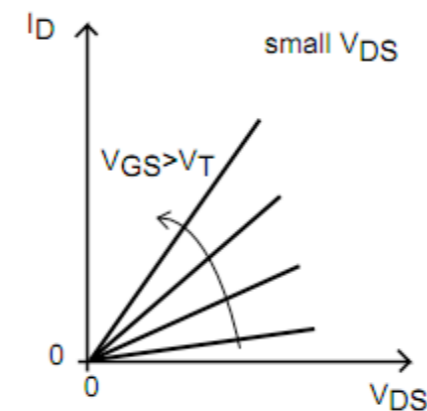
□ *Linear or Triode regime:*

- MOSFET: $V_{GS} > V_T$, $V_{GD} > V_T$, with $V_{DS} > 0$.
- Water analogy: gate open but small difference in height between source and drain; water flows.



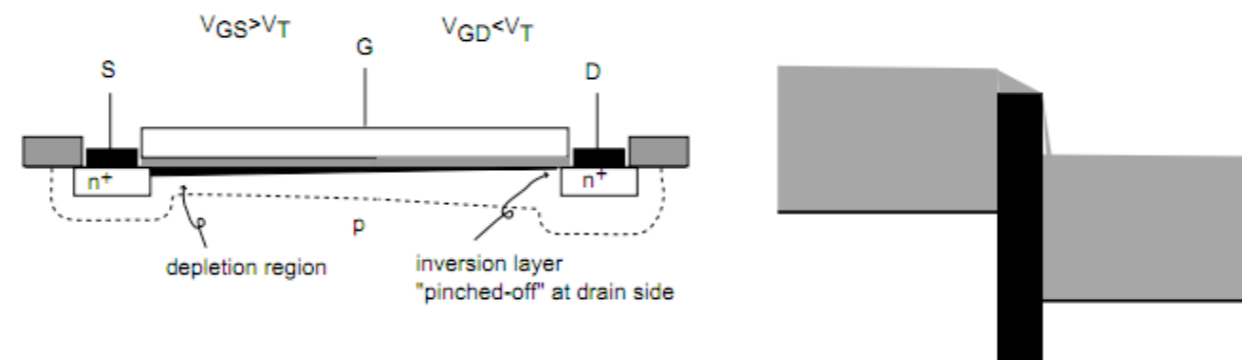
Electrons drift from source to drain \Rightarrow electrical current!

- $V_{GS} \uparrow \rightarrow |Q_n| \uparrow \rightarrow I_D \uparrow$
- $V_{DS} \uparrow \rightarrow E_y \uparrow \rightarrow I_D \uparrow$

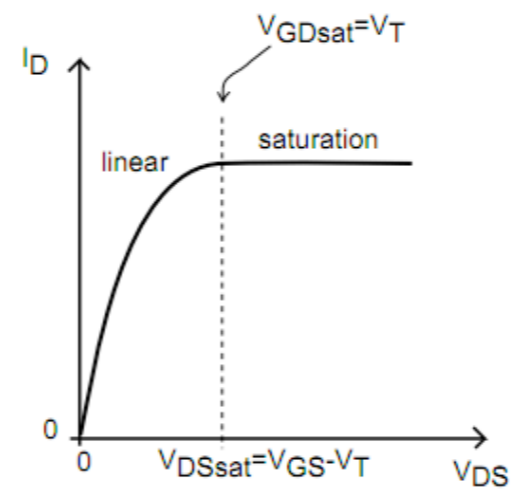


□ *Saturation regime:*

- MOSFET: $V_{GS} > V_T$, $V_{GD} < V_T$ ($V_{DS} > 0$).
- Water analogy: gate open; water flows from source to drain, but free-drop on drain side \Rightarrow total flow independent of relative reservoir height!



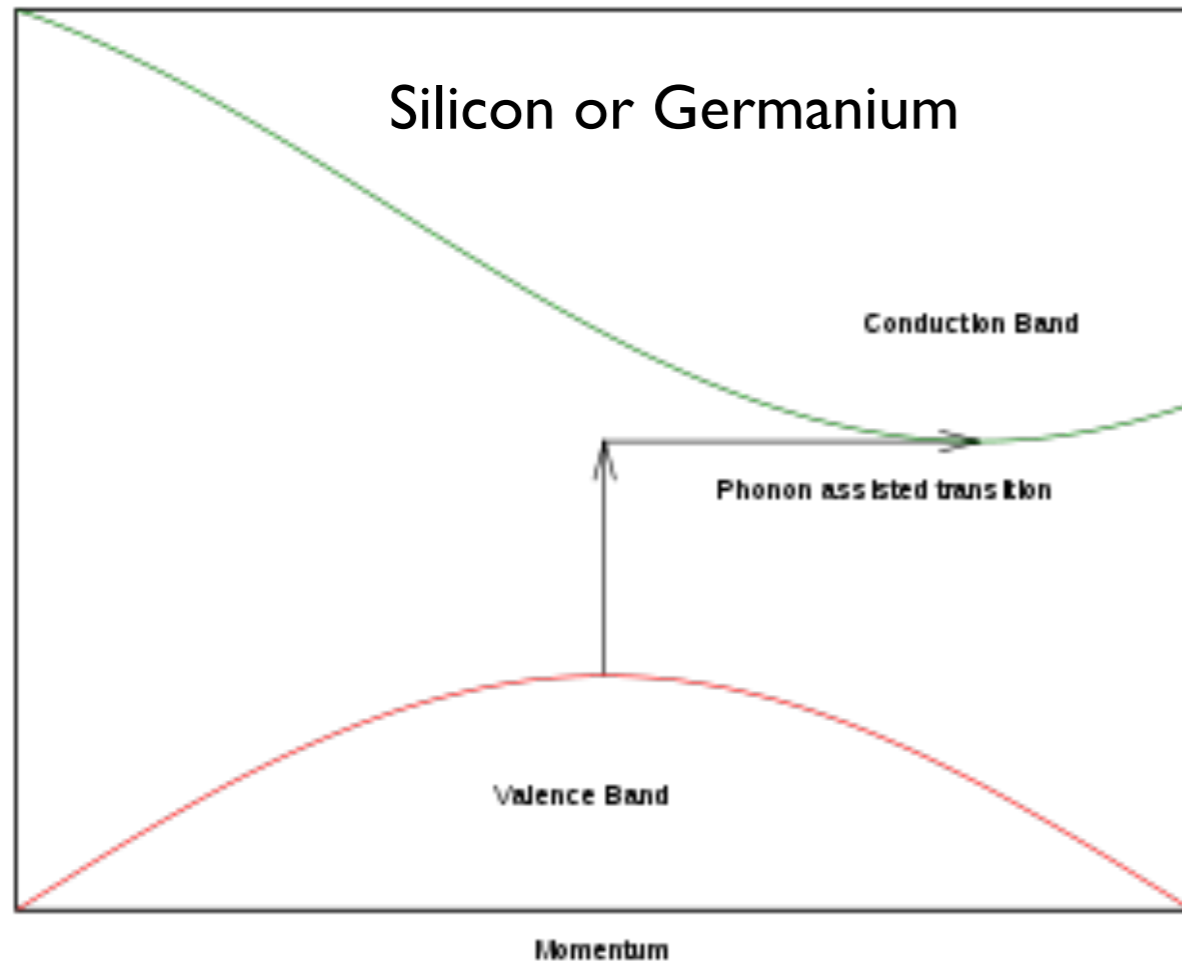
I_D independent of V_{DS} : $I_D = I_{Dsat}$



Indirect versus Direct Band Gap Semiconductors

Photovoltaics

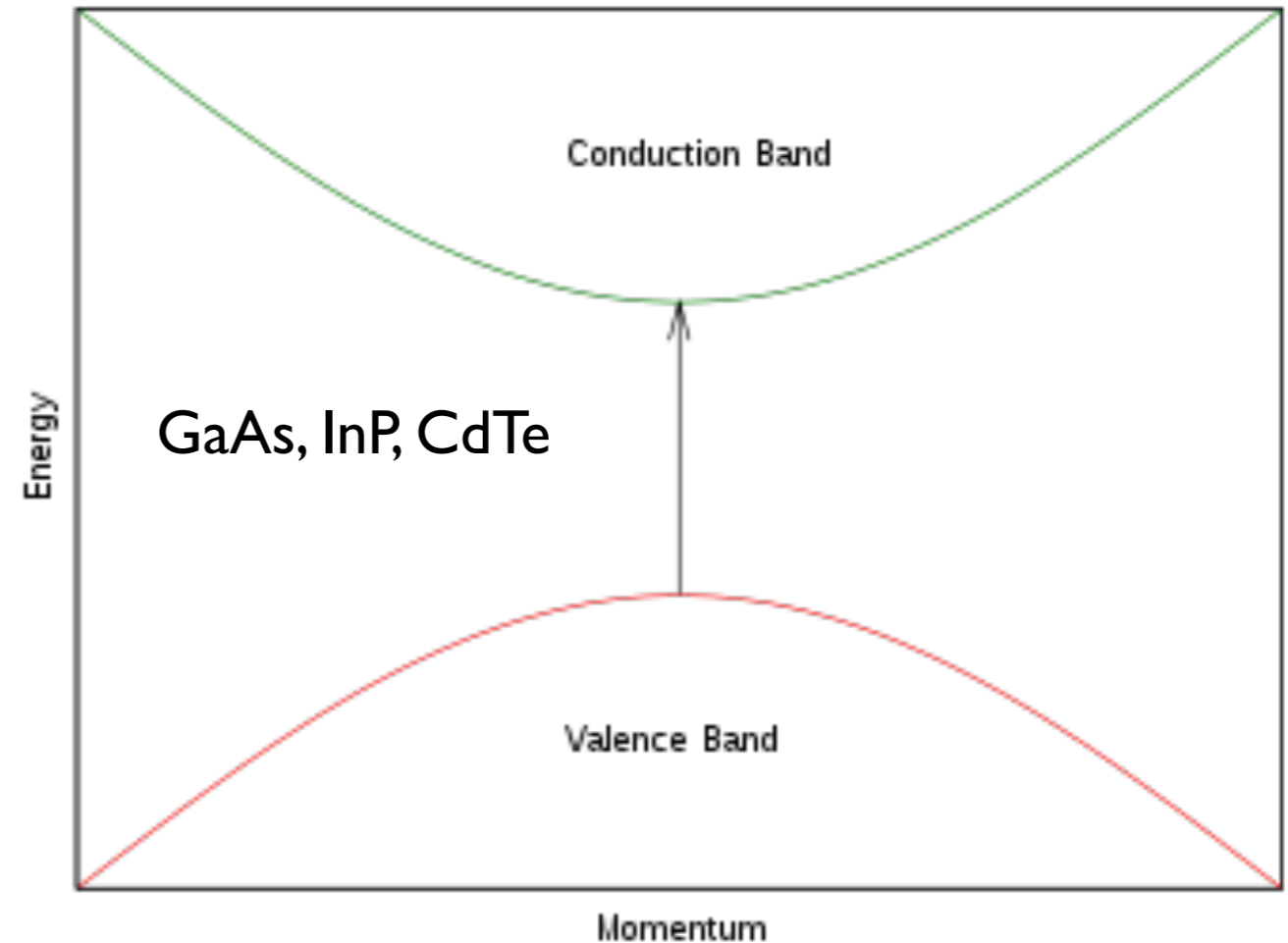
Indirect Band Gap



Energy vs. [crystal momentum](#) for a semiconductor with an indirect band gap, showing that an electron cannot shift from the lowest-energy state in the conduction band (green) to the highest-energy state in the valence band (red) without a change in momentum. Here, almost all of the energy comes from a [photon](#) (vertical arrow), while almost all of the momentum comes from a [phonon](#) (horizontal arrow).

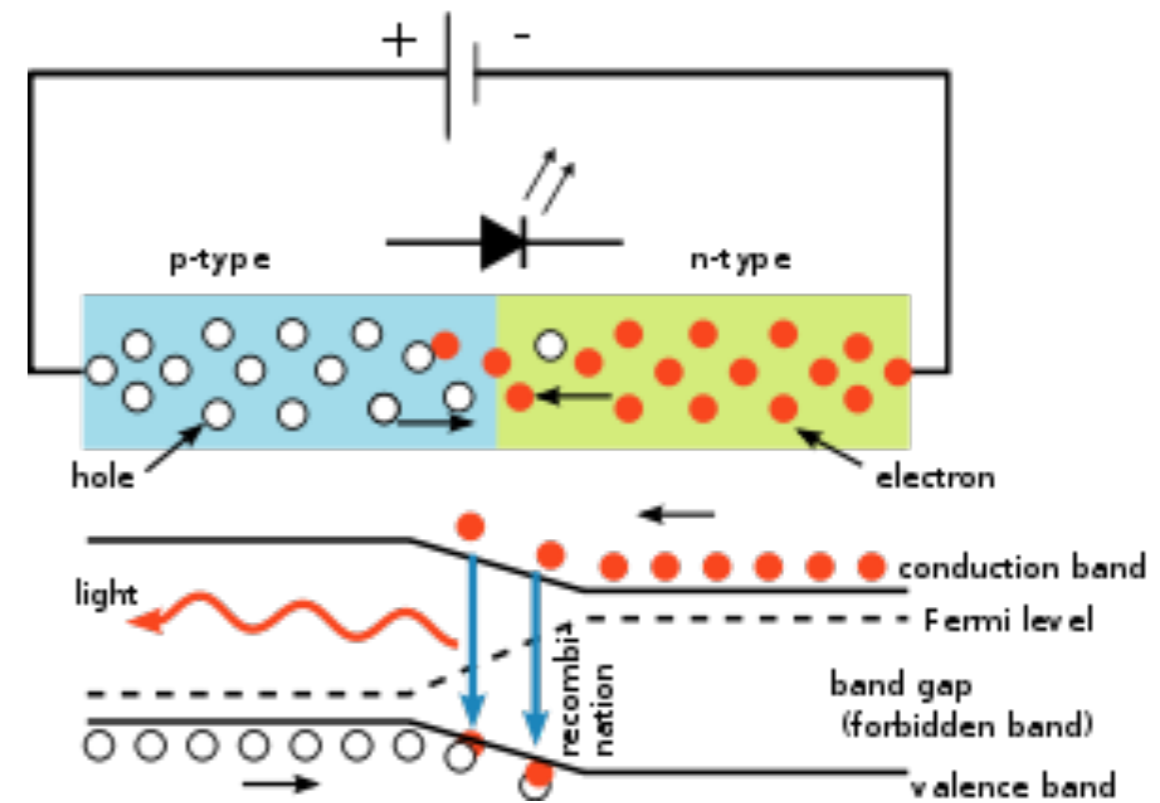
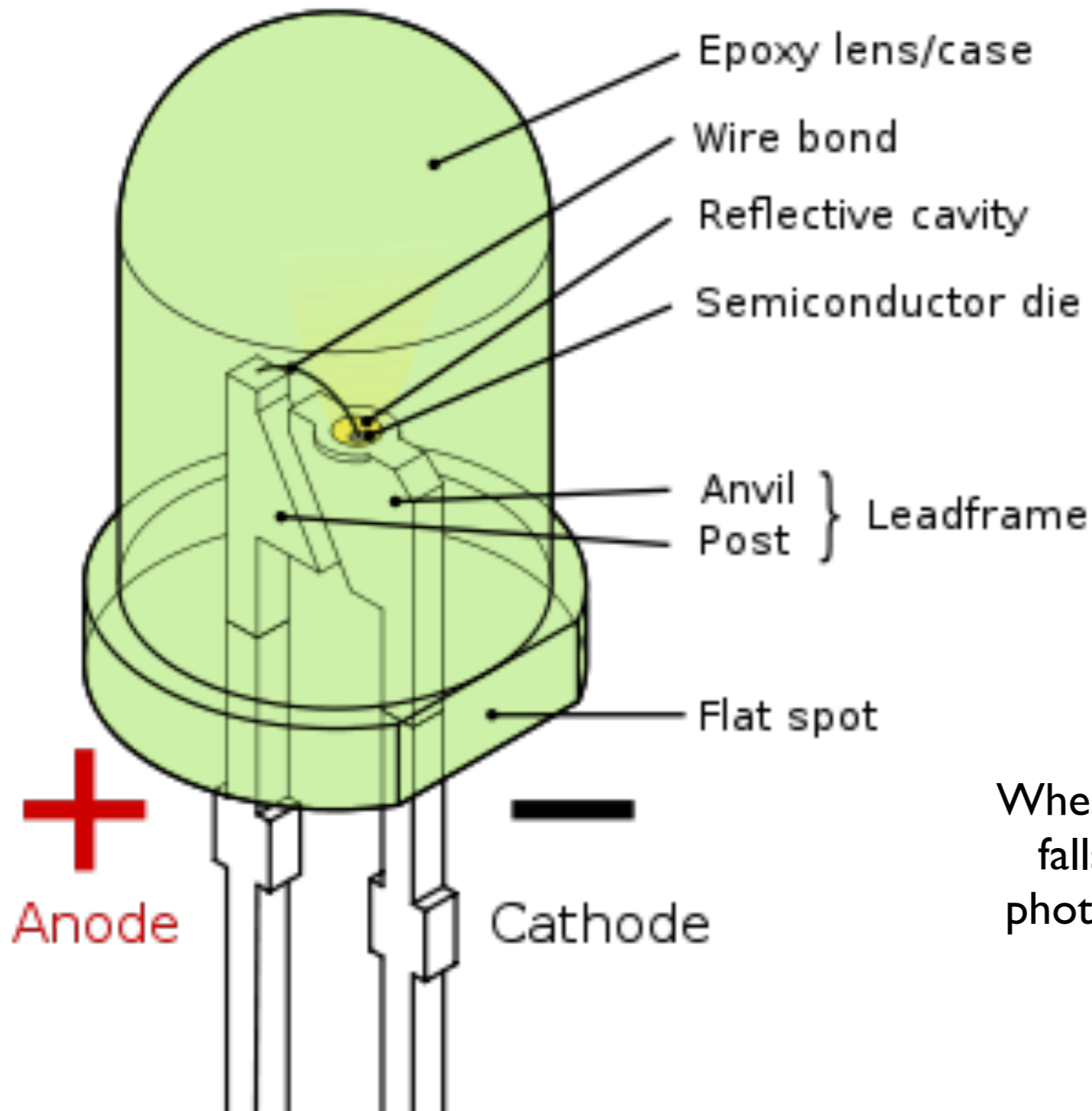
LEDs

Direct Band Gap



Energy vs. [crystal momentum](#) for a semiconductor with a direct band gap, showing that an electron can shift from the lowest-energy state in the conduction band (green) to the highest-energy state in the valence band (red) without a change in [crystal momentum](#). Depicted is a transition in which a photon excites an electron from the valence band to the conduction band.

Light Emitting Diode (LED)



When a hole meets an electron the electron falls into a lower energy level releasing a photon with energy related to the band gap

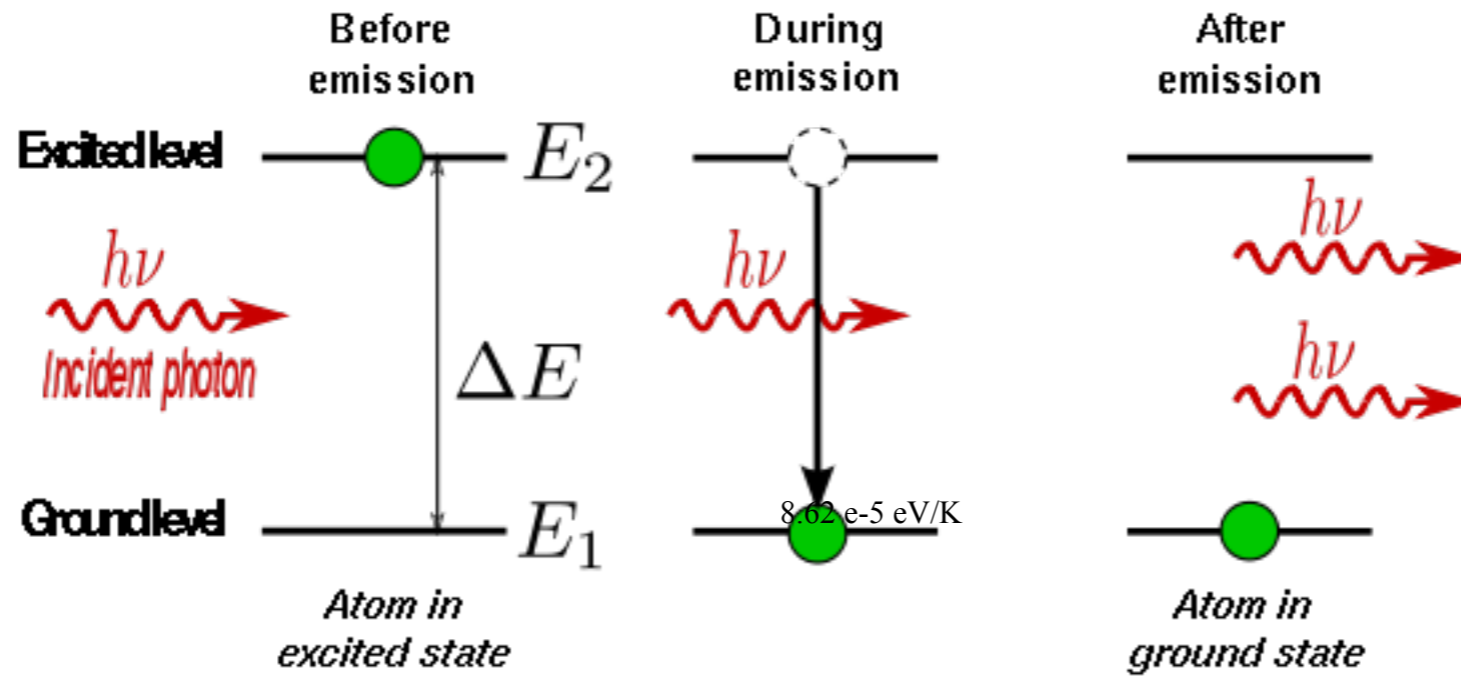
This can be IR, visible or near UV

Light Emitting Diode (LED)

Color	Wavelength [nm]	Voltage [V]	Semiconductor material
Infrared	$\lambda > 760$	$\Delta V < 1.9$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
Red	$610 < \lambda < 760$	$1.63 < \Delta V < 2.03$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Orange	$590 < \lambda < 610$	$2.03 < \Delta V < 2.10$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Yellow	$570 < \lambda < 590$	$2.10 < \Delta V < 2.18$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Green	$500 < \lambda < 570$	$1.9^{[47]} < \Delta V < 4.0$	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)
Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate – (under development)
Violet	$400 < \lambda < 450$	$2.76 < \Delta V < 4.0$	Indium gallium nitride (InGaN)
Purple	multiple types	$2.48 < \Delta V < 3.7$	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
Ultraviolet	$\lambda < 400$	$3.1 < \Delta V < 4.4$	Diamond (235 nm) ^[48] Boron nitride (215 nm) ^{[49][50]} Aluminium nitride (AlN) (210 nm) ^[51] Aluminium gallium nitride (AlGaInN) Aluminium gallium indium nitride (AlGaInN) – (down to 210 nm) ^[52]
White	Broad spectrum	$\Delta V = 3.5$	Blue/UV diode with yellow phosphor

Laser Diode

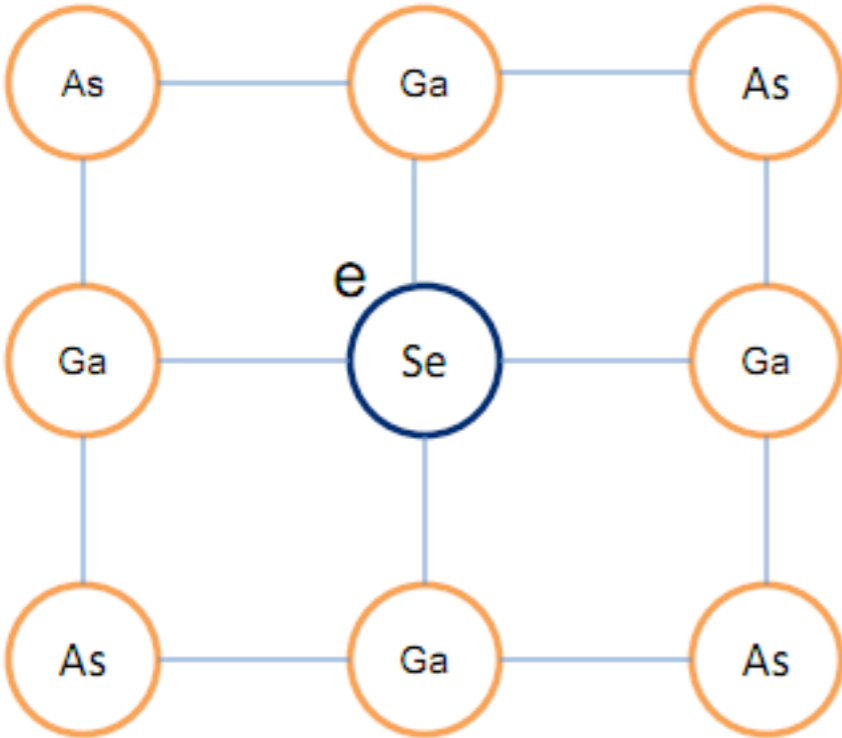
Stimulated Emission



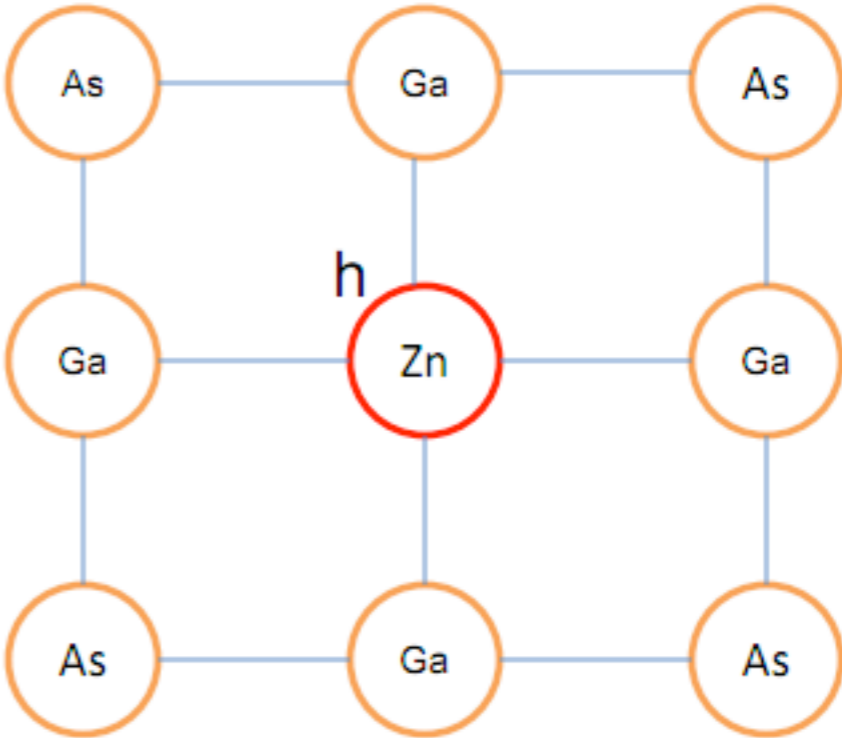
$$E_2 - E_1 = \Delta E = h\nu$$

Optical Cavity formed by parallel sided crystal that forms a waveguide with reflective ends

Laser Diode



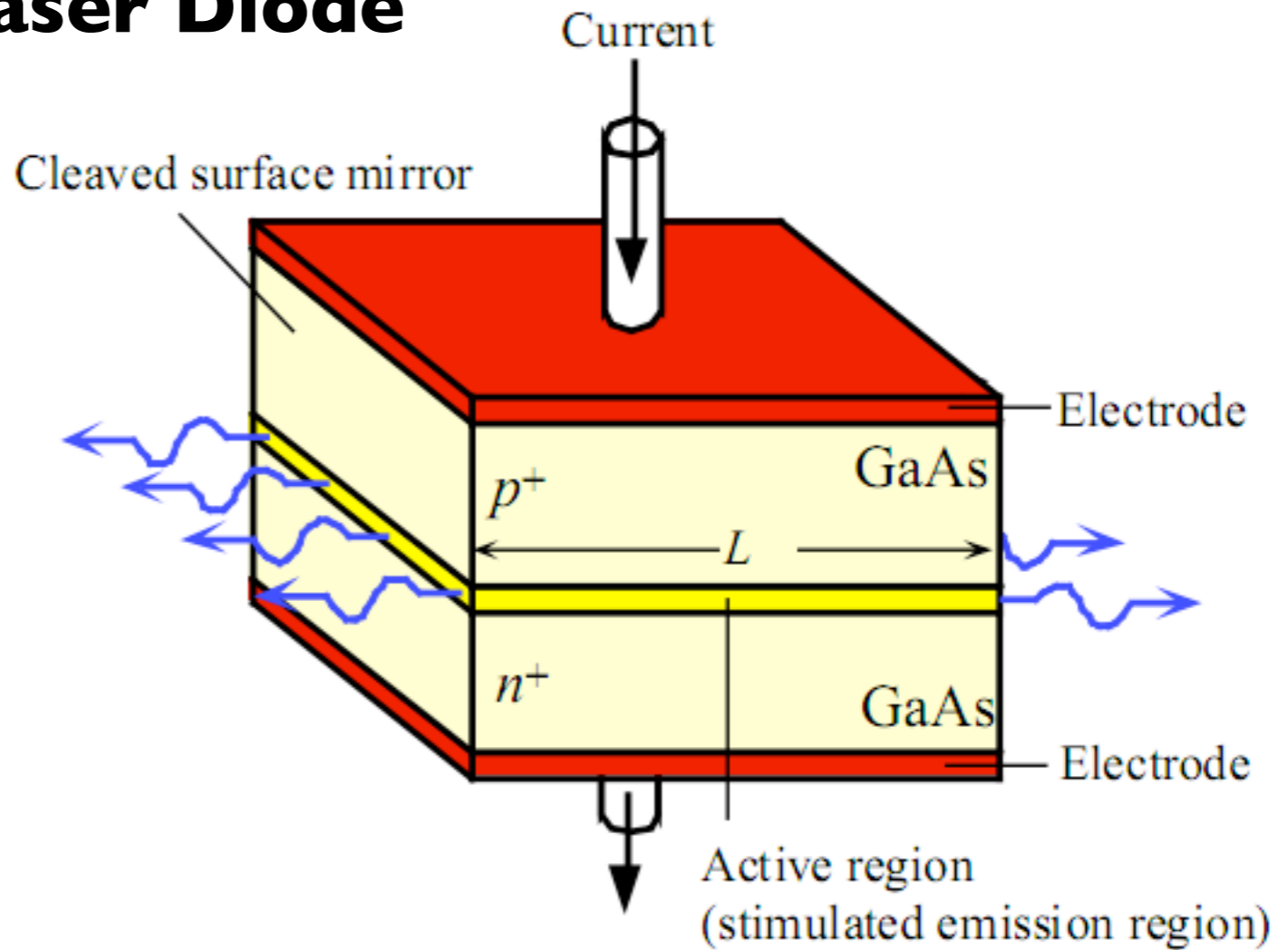
n-doped



p-doped

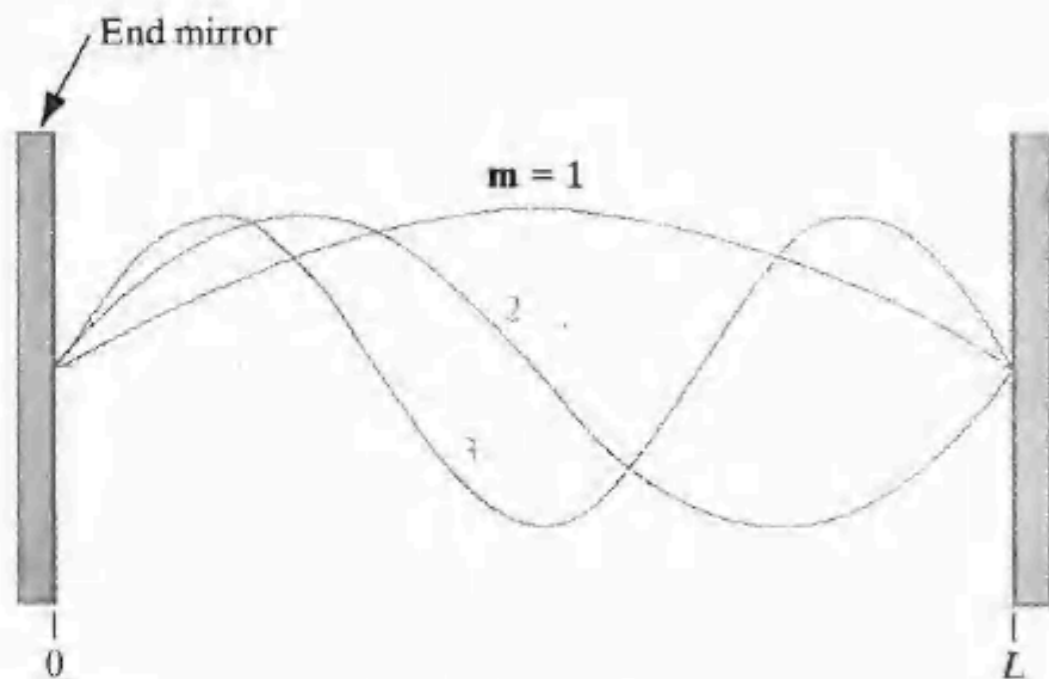
Laser Diode

An adequate forward bias is required to inject carriers across the junction to initiate population inversion. The process is called *injection pumping*.



A schematic illustration of a GaAs homojunction laser diode. The cleaved surfaces act as reflecting mirrors.

© 1999 S.O. Kasap, *Optoelectronics* (Prentice Hall)



Laser Diode

Laser diode material (active region / substrate)	Typical emission wavelengths	Typical application
InGaN / GaN, SiC	380, 405, 450, 470 nm	data storage
AlGaInP / GaAs	635, 650, 670 nm	laser pointers, DVD players
AlGaAs / GaAs	720–850 nm	CD players, laser printers
InGaAs / GaAs	900–1100 nm	pumping EDFAs; high-power VECSELs
InGaAsP / InP	1000–1650 nm	optical fiber communications

Semiconducting Polymers

Conductivity

S/cm

10^6

10^4

10^2

1

10^{-2}

10^{-4}

10^{-6}

10^{-8}

10^{-10}

10^{-12}

10^{-14}

10^{-16}

Copper

Doped rr PATs

Silicon

rr PATs



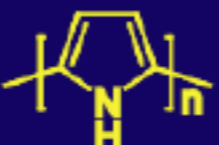
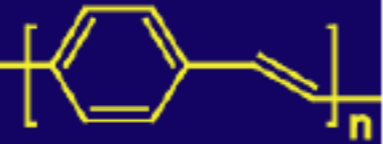
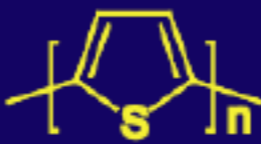
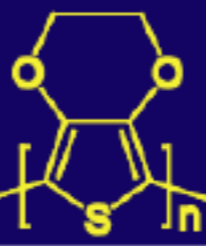
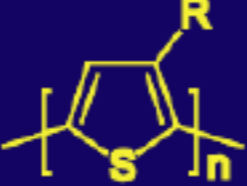
Glass

Polyethylene

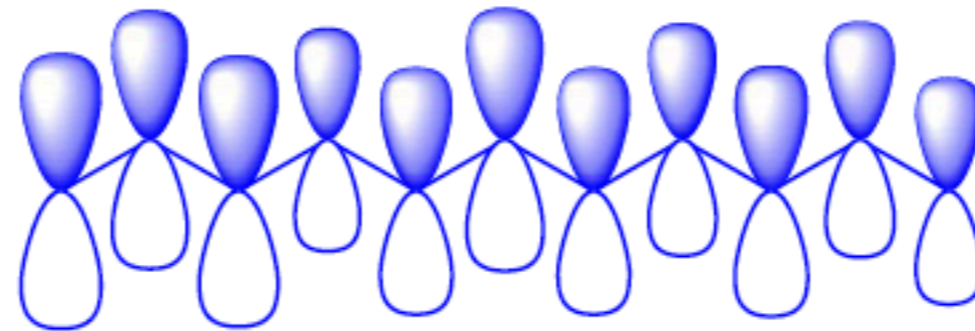
Conductors

Semiconductors

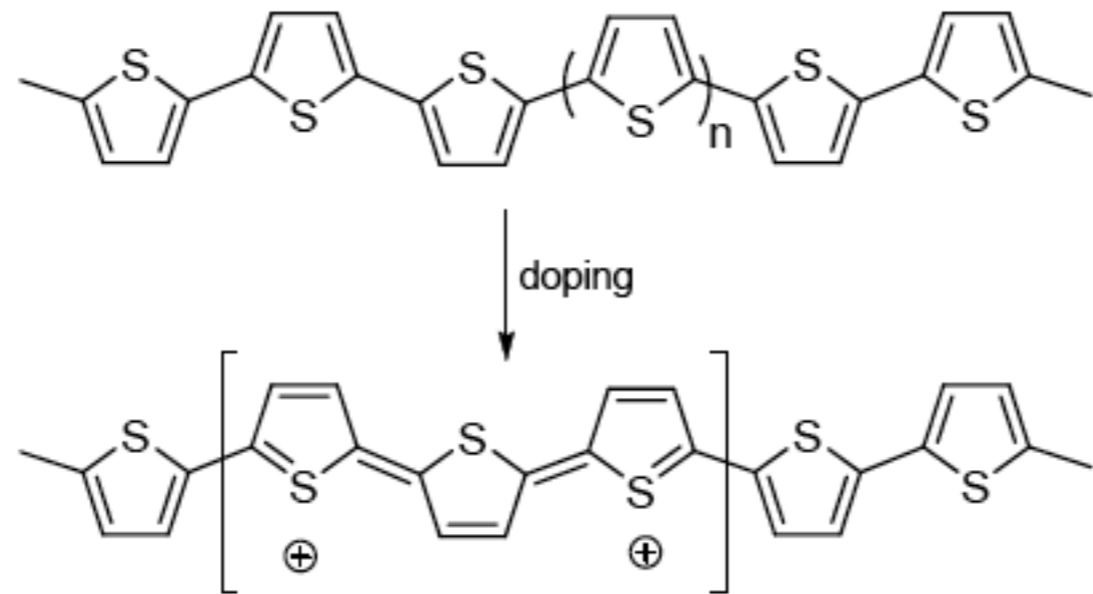
Insulators

1977		Polyacetylene
1979		Poly(p-phenylene)
1979		Polypyrrole
1979		Poly(p-phenylene vinylene)
1982		Polythiophene
1989		Poly(3,4-ethylene dioxathiophene) PEDOT
1992		Regioregular Poly(3-alkyl thiophene)(rr-PATs)

Semiconducting Polymers



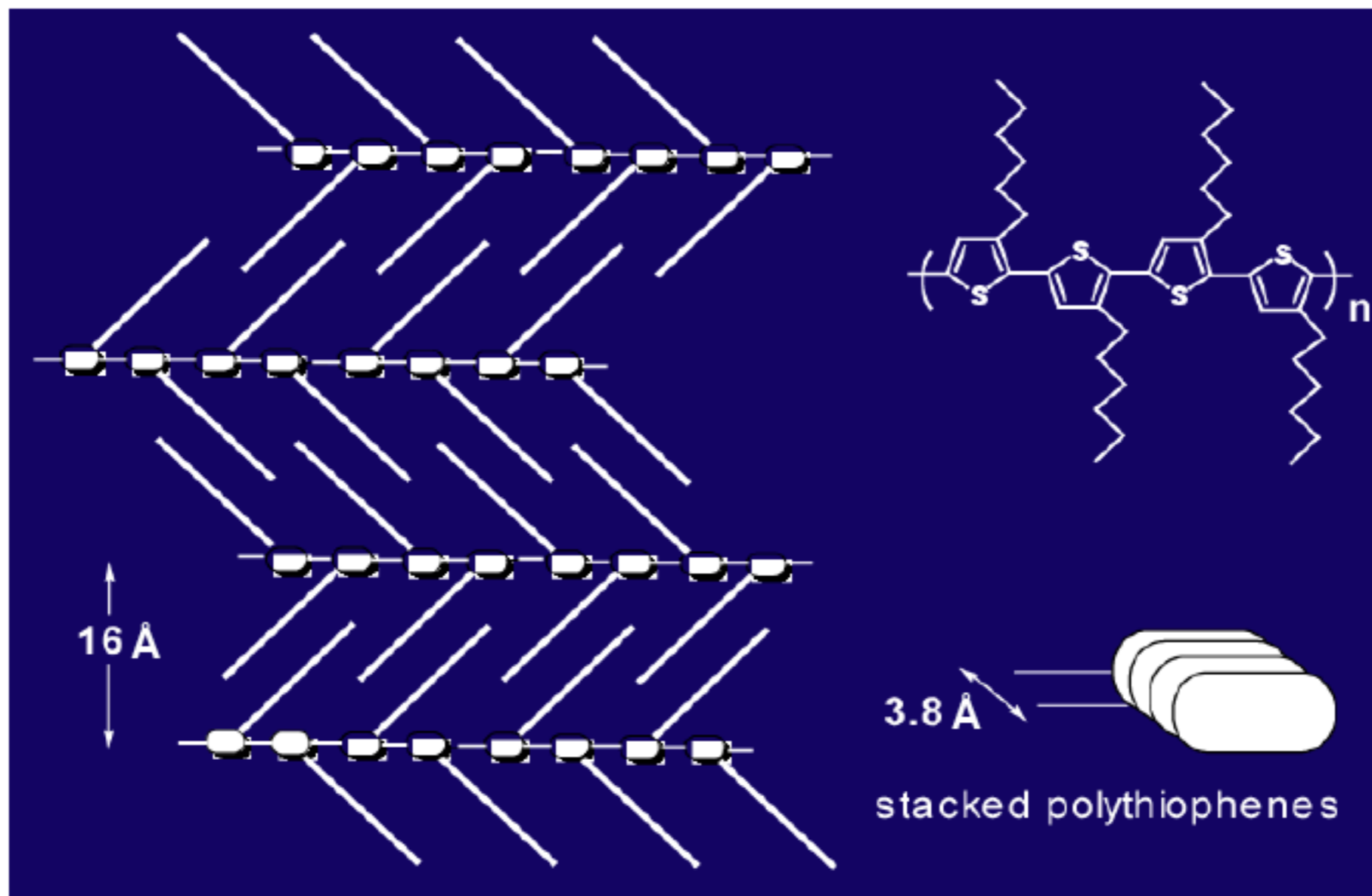
- sp^2 hybridized C have p_z orbitals that line up to form connected electron clouds where electrons/holes can travel through.
- And when doped with an oxidant → p-type semiconducting polymers → holes are the charges.



$\sigma = 10^{-6} - 10^{-8} \text{ S/cm}$
semiconductor

$\sigma = 10 - 10^3 \text{ S/cm}$
conductor

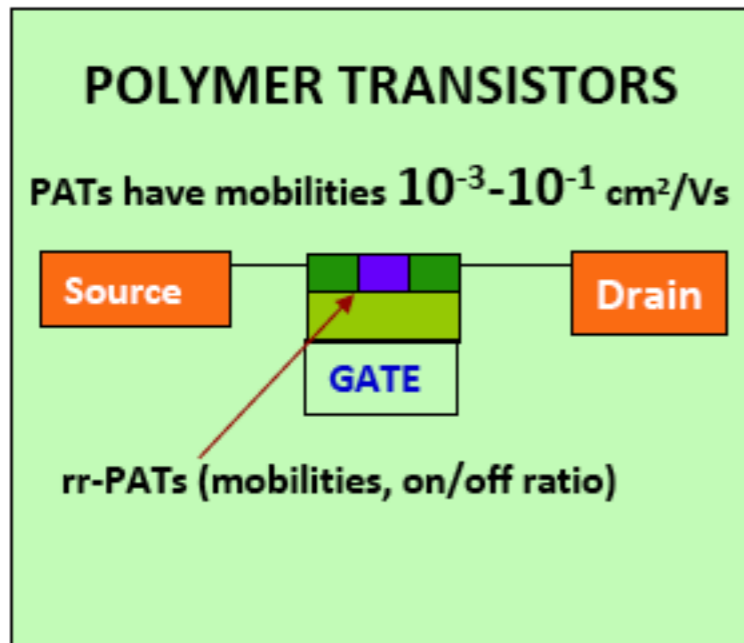
Regioregular Poly(3-Alkylthiophene) (PATs)



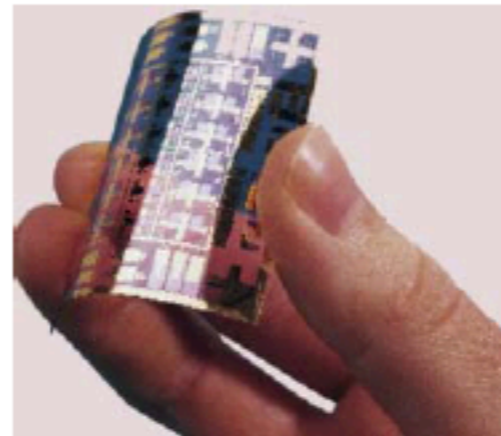
rr PATs self-assemble to form flat stacks resulting in high conductivities upon doping.

McCullough, R. D.; Tristram-Nagle, S.; Williams, S. P.; Lowe, R. D.; Jayaraman, M. *J. Am. Chem. Soc.* 1993, 115, 4910

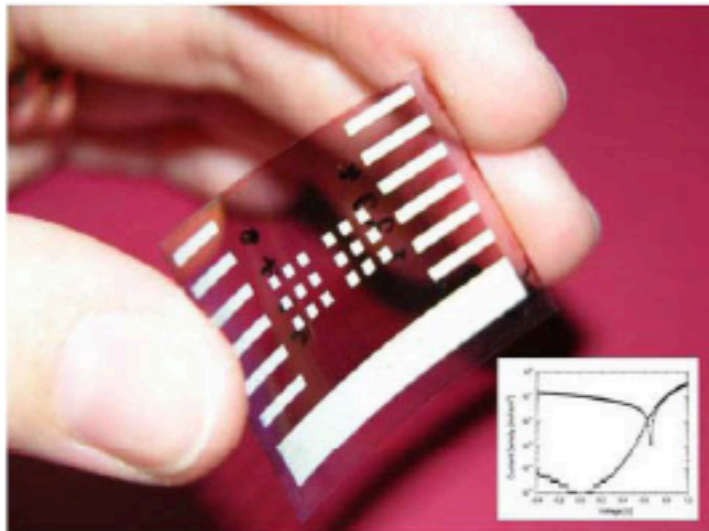
Applications of Semiconducting Polymers



Plastic Field-Effect Transistors



Polymer Solar Cell



Organic Light-Emitting Diodes (LEDs)



organic-inorganic hybrid solar cell

