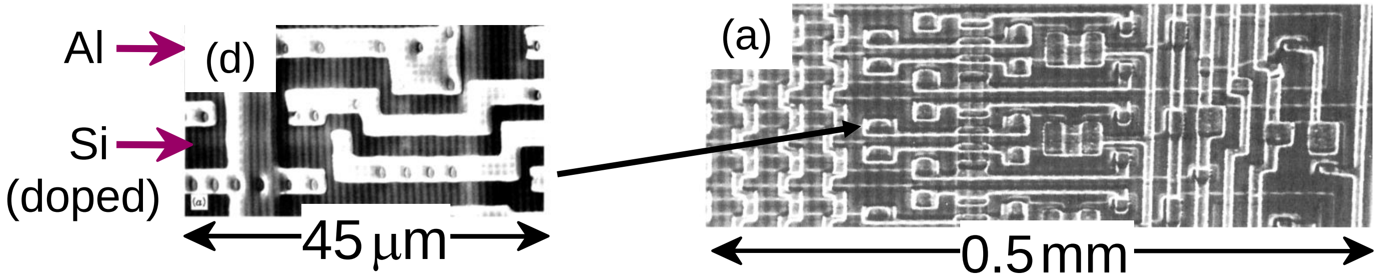
Electrical Properties of Materials

View of an Integrated Circuit

- Scanning electron micrographs of an IC:



- A dot map showing location of Si (a semiconductor):
  -- Si shows up as light regions.

- A dot map showing location of Al (a conductor):
  -- Al shows up as light regions.

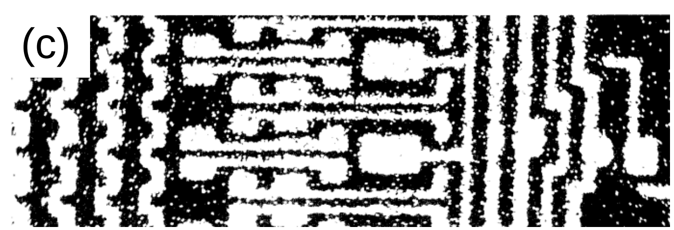


Fig. (d) from Fig. 12.27(a), *Callister & Rethwisch 3e.* (Fig. 12.27 is courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

Figs. (a), (b), (c) from Fig. 18.27, *Callister & Rethwisch 8e.*

Electrical Conduction

- Ohm's Law: $V = \boldsymbol{I} R$

voltage drop (volts = J/C)
C = Coulomb

current (amps = C/s)

resistance (Ohms)

- Resistivity, ρ:

-- a material property that is independent of sample size and geometry

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

surface area of current flow

current flow path length

- Conductivity, σ

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

Definitions

Further definitions

$\boxed{J = \sigma\ \varepsilon}$ <= another way to state Ohm's law

$J \equiv$ current density $= \dfrac{\text{current}}{\text{surface area}} = \dfrac{I}{A}$ like a flux

$\varepsilon \equiv$ electric field potential $= V/\ell$

$$J = \sigma\,(V/\ell\,)$$

Electron flux conductivity voltage gradient

Conductivity: Comparison

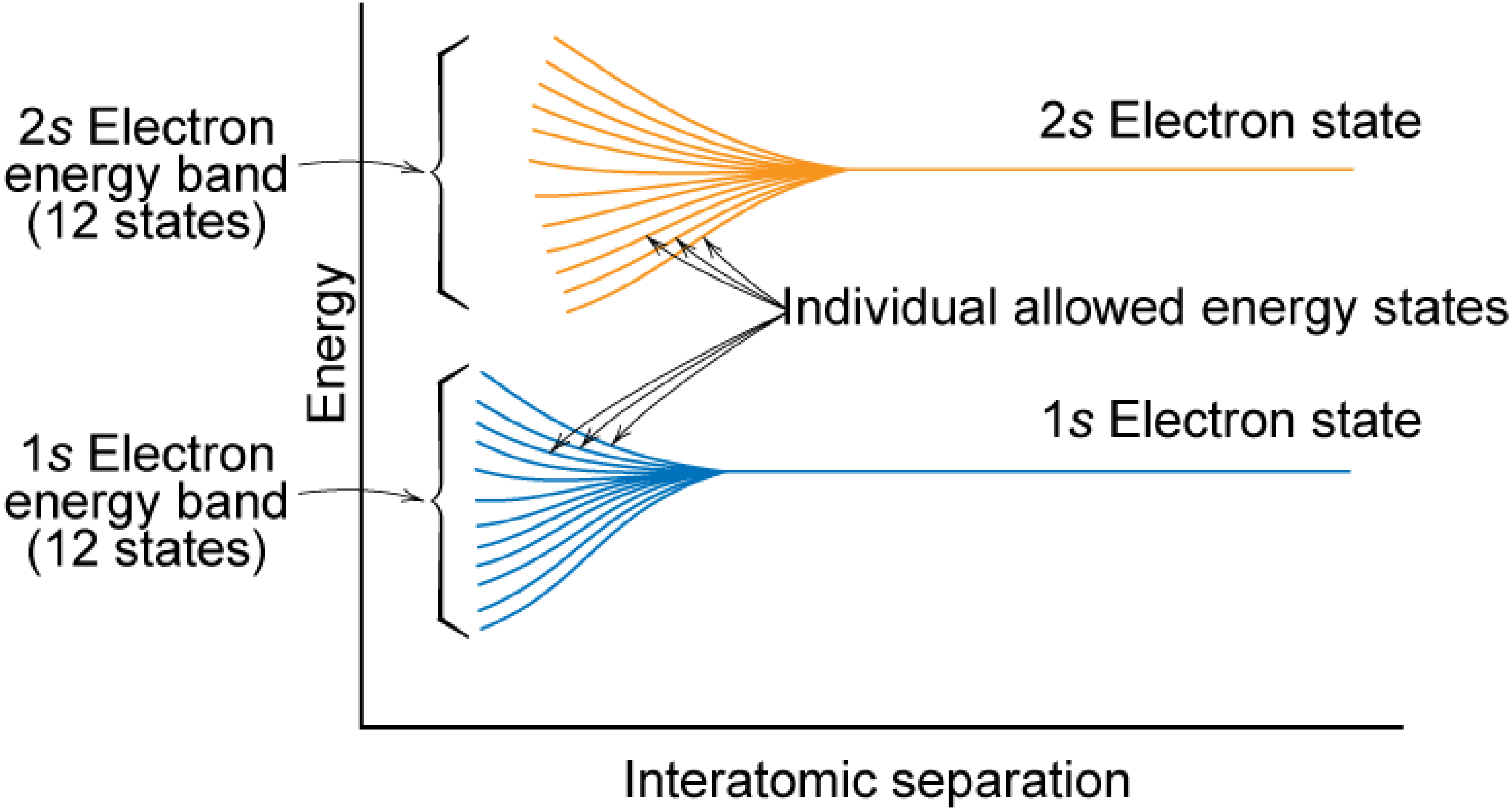
- Room temperature values $(\text{Ohm-m})^{-1} = (\Omega - \text{m})^{-1}$

METALS	conductors	CERAMICS	
Silver	6.8×10^{7}	Soda-lime glass	10^{-10}-10^{-11}
Copper	6.0×10^{7}	Concrete	10^{-9}
Iron	1.0×10^{7}	Aluminum oxide	$<10^{-13}$

SEMICONDUCTORS		POLYMERS	
Silicon	4×10^{-4}	Polystyrene	$<10^{-14}$
Germanium	2×10^{0}	Polyethylene	10^{-15}-10^{-17}
GaAs	10^{-6}		
	semiconductors		insulators

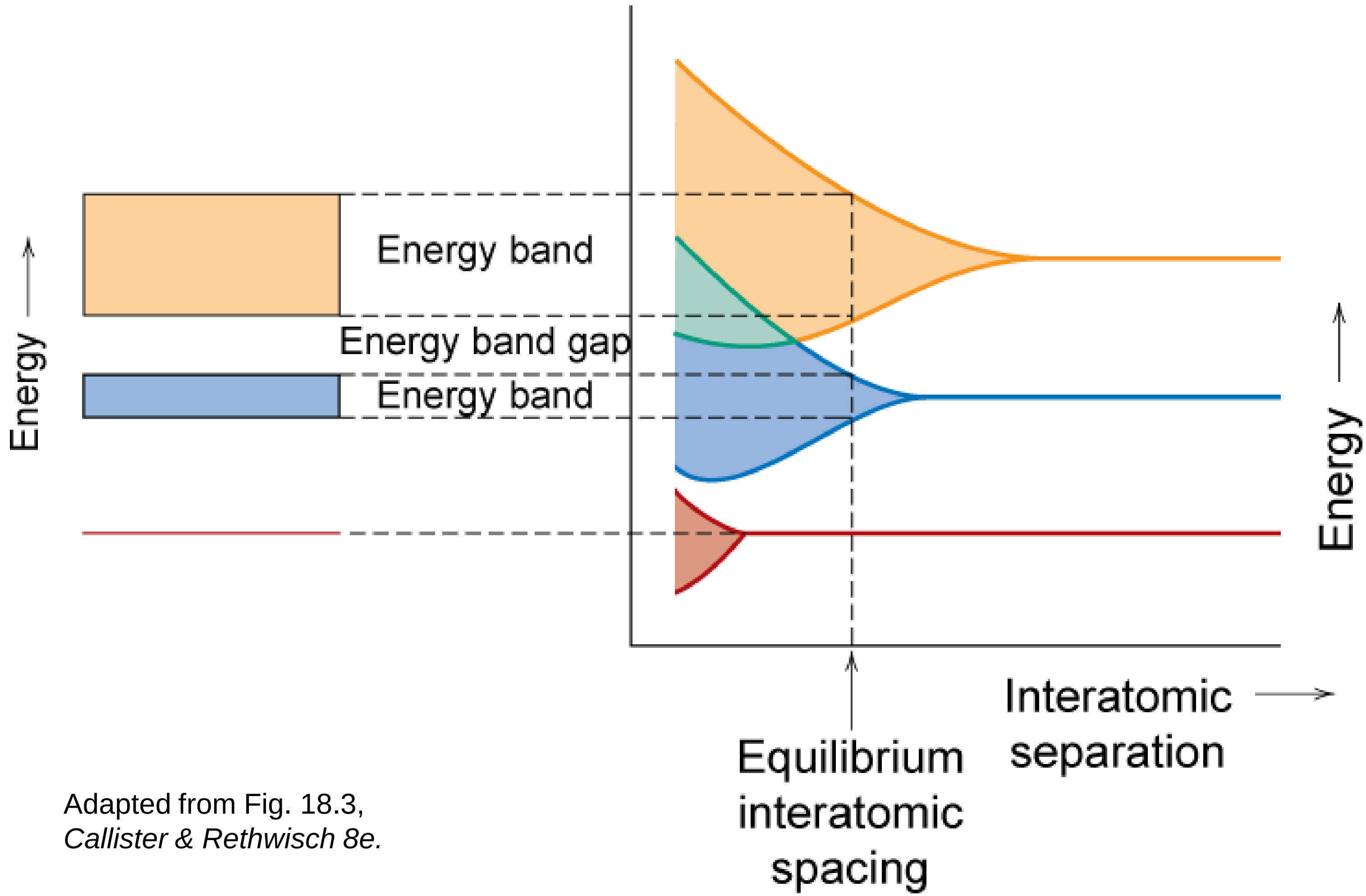
Selected values from Tables 18.1, 18.3, and 18.4, *Callister & Rethwisch 8e.*

Electron Energy Band Structures

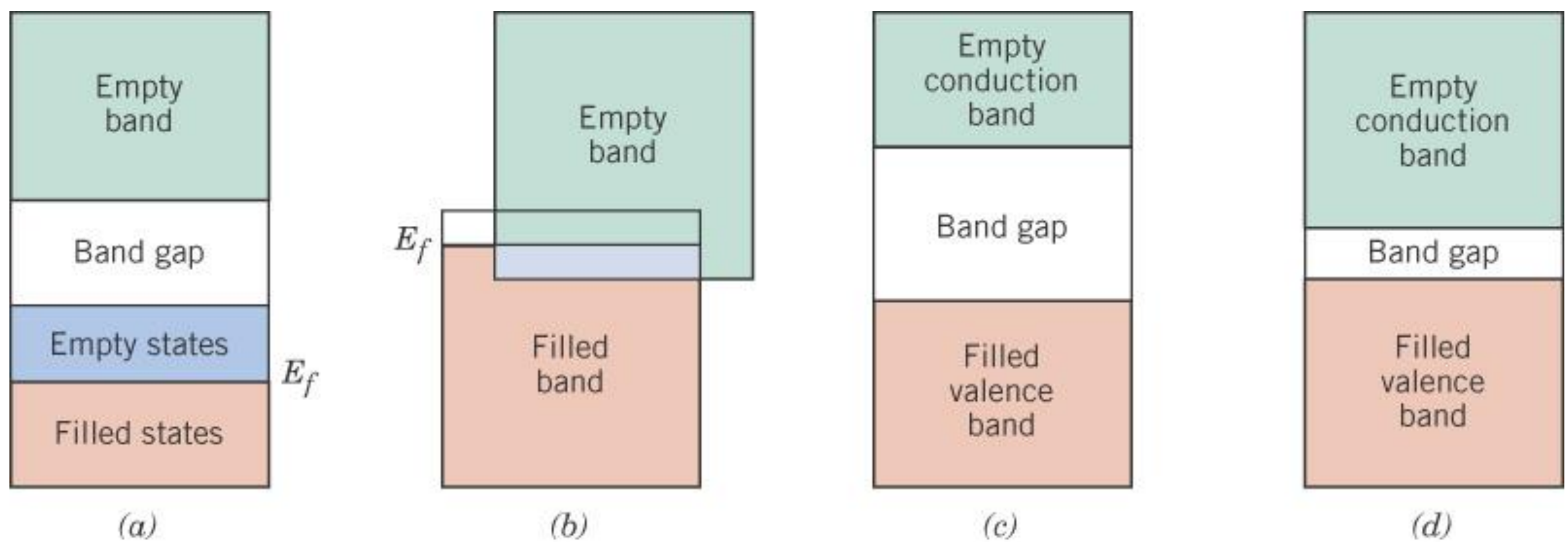


Adapted from Fig. 18.2, *Callister & Rethwisch 8e.*

Band Structure Representation



Adapted from Fig. 18.3,
Callister & Rethwisch 8e.


Empty
band
Band gap
Empty states
E_f
Filled states
(a)
Empty
band
E_f
Filled
band
(b)
Empty
conduction
band
Band gap
Filled
valence
band
(c)
Empty
conduction
band
Band gap
Filled
valence
band
(d)

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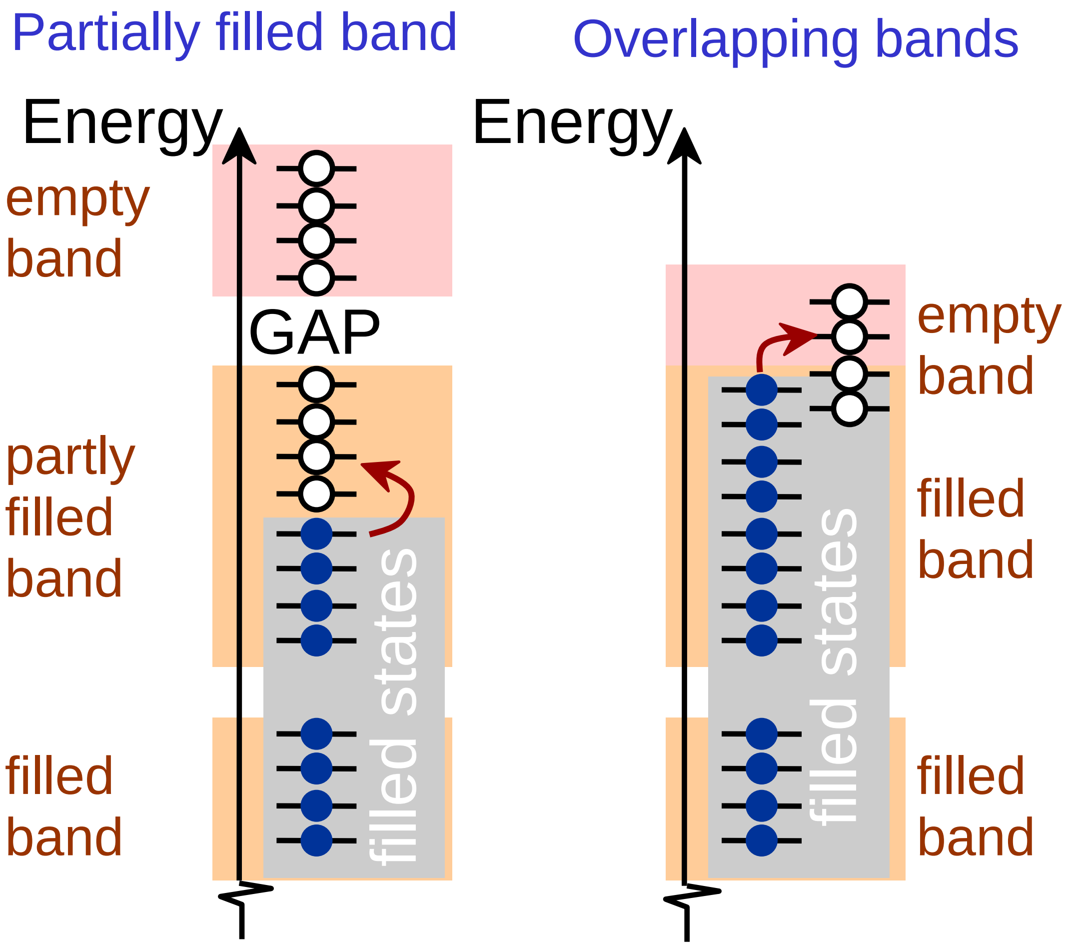
Conduction & Electron Transport

- Metals (Conductors):

-- for metals empty energy states are adjacent to filled states.

-- thermal energy excites electrons into empty higher energy states.

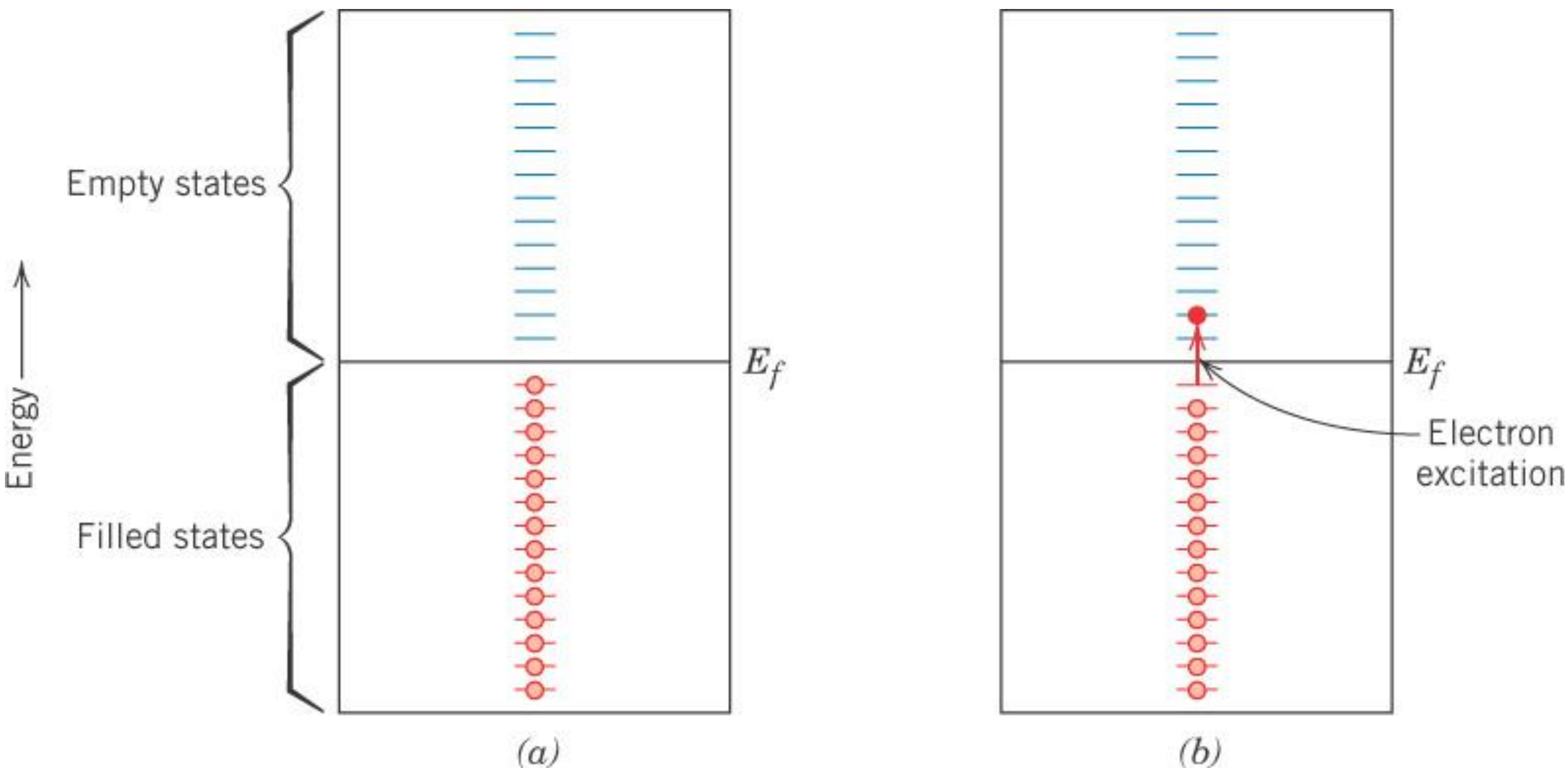
-- two types of band structures for metals
- partially filled band
- empty band that overlaps filled band



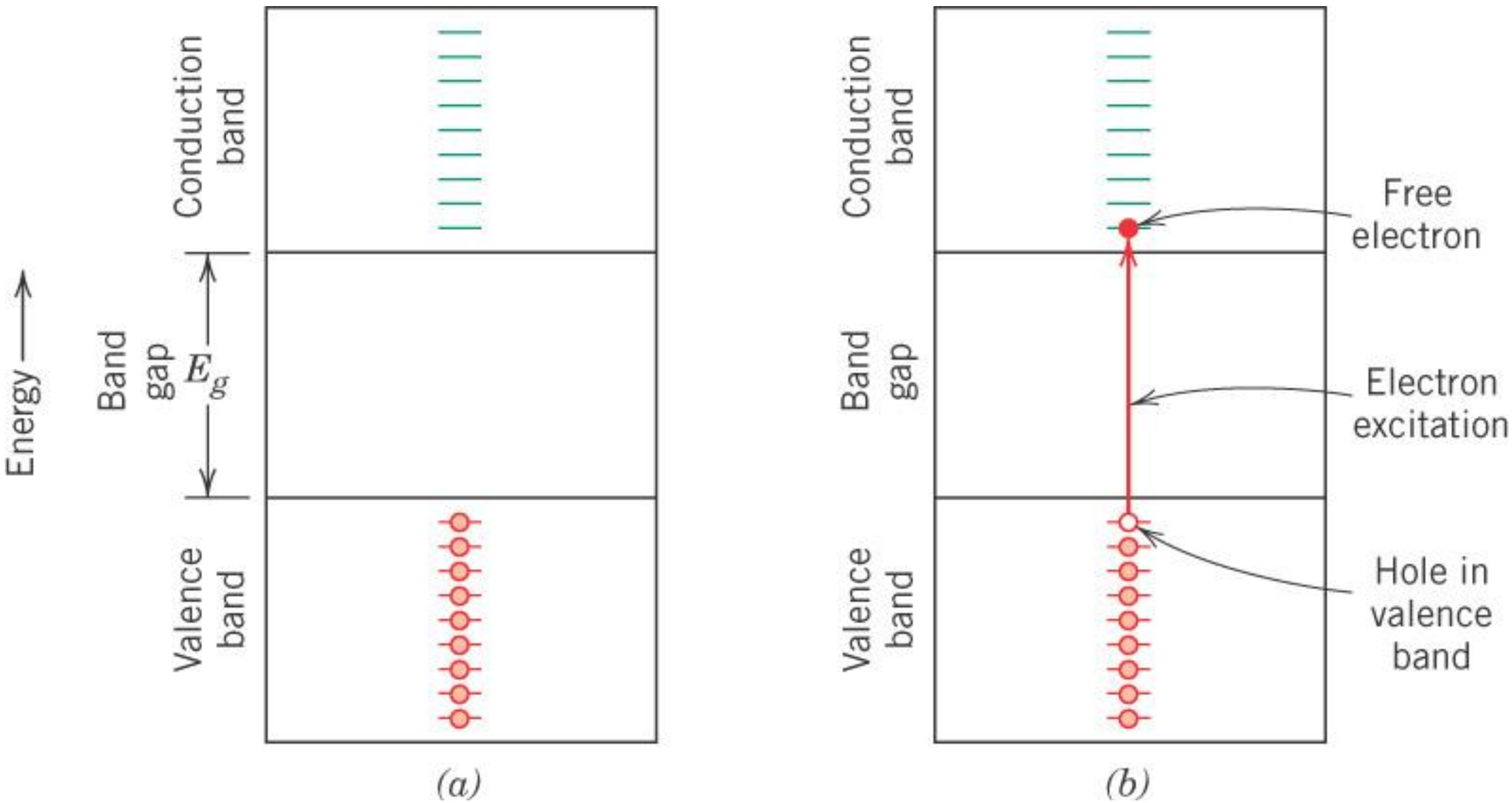
12.6 Conduction in Terms of Band and Atomic Bonding Models

Metallic character

Excitation barrier is much smaller than heat (RT), noise or any background excitations. Practically anything excite electrons to the conduction band



An intrinsic semiconductor has a band gap or barrier for the electrons to get into the conduction band
This barrier need a photon excitation, an external bias potential
Usually RT cannot excite the electron to the conduction band.
For instance, a photon of light ~4eV



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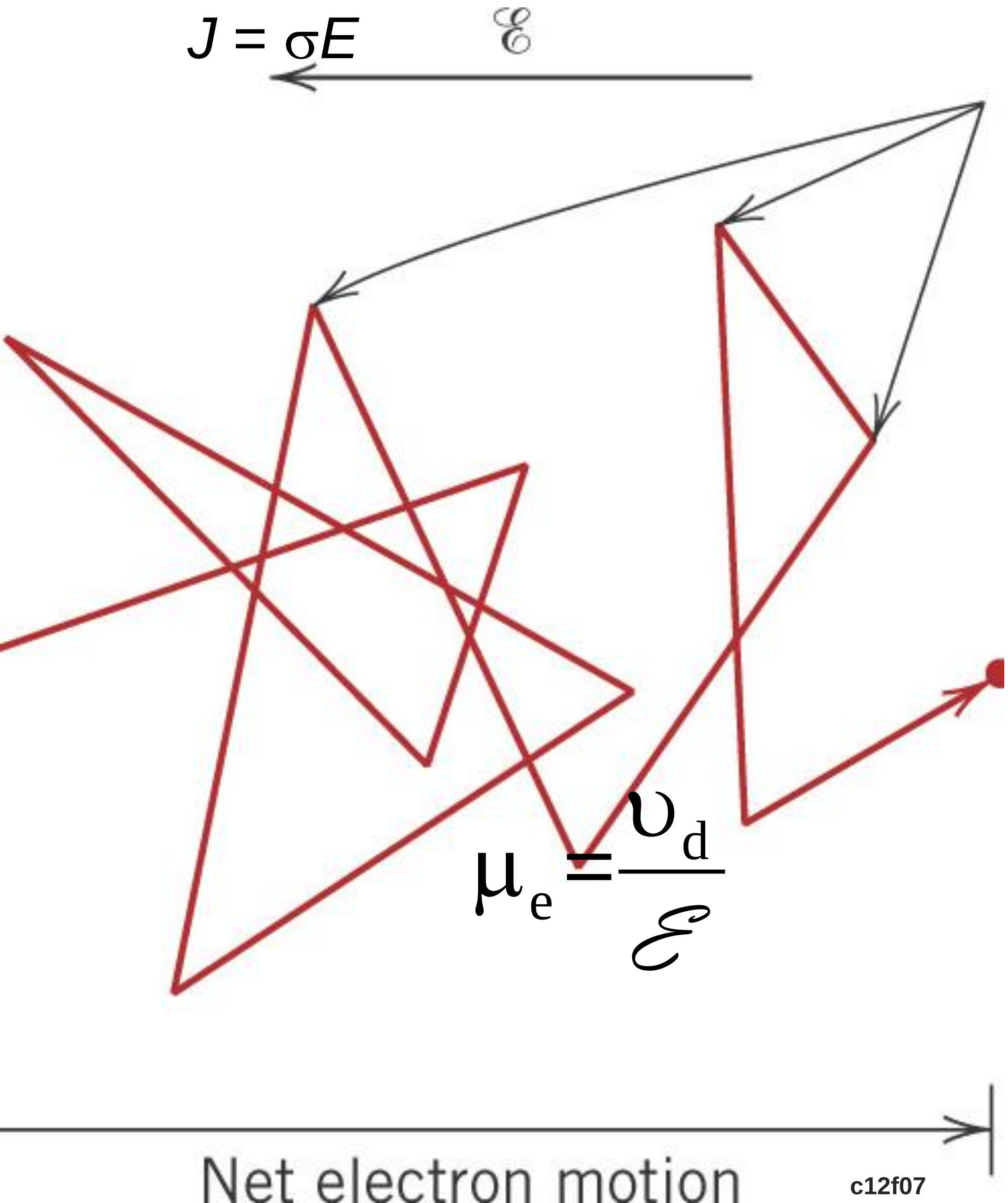
12.7 Electron Mobility



$$\mu_e = \frac{\upsilon_d}{\mathscr{E}}$$

Scattering Events

Electric field drifts electrons in the opposite direction to the field

b/c electrons are –ve

The actual speed of electrons is much higher than the drift velocity

Scattering is due to the strike with the nuclei

12.7 Electron Mobility

When the actual velocity of the electrons is similar to the drift velocity, the system is in the ballistic regime

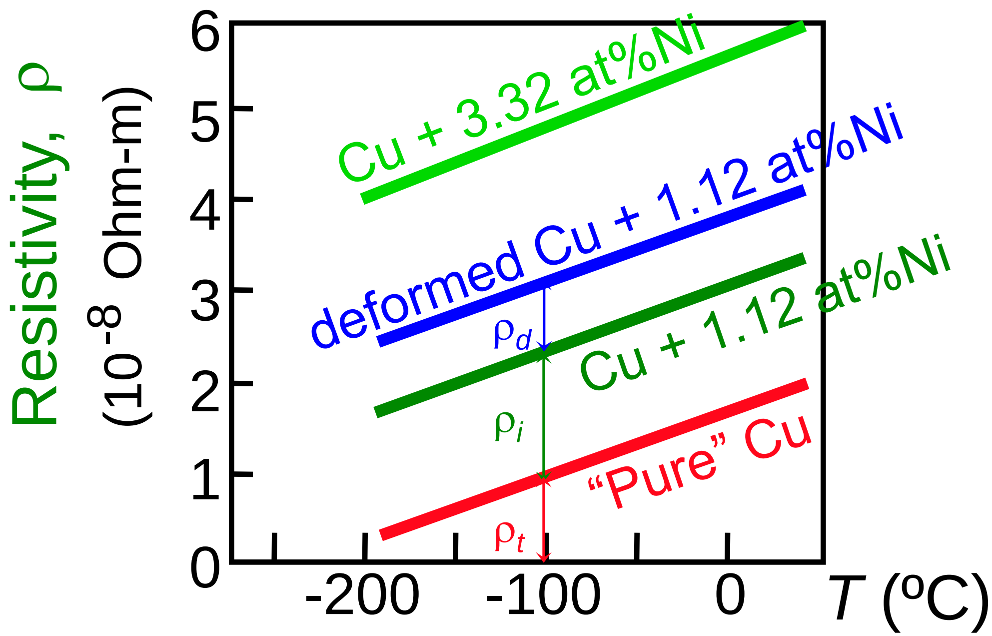
In the ballistic regime there is practically no barrier for the electrons

Examples: in vacuum tubes, ~in carbon nanotubes (CNT), superconductors*

Metals: Influence of Temperature and Impurities on Resistivity

- Presence of imperfections increases resistivity
  - -- grain boundaries
  - -- dislocations
  - -- impurity atoms
  - -- vacancies

These act to scatter electrons so that they take a less direct path.



Adapted from Fig. 18.8, *Callister & Rethwisch 8e.* (Fig. 18.8 adapted from J.O. Linde, *Ann. Physik* **5**, p. 219 (1932); and C.A. Wert and R.M. Thomson, *Physics of Solids*, 2nd ed., McGraw-Hill Book Company, New York, 1970.)

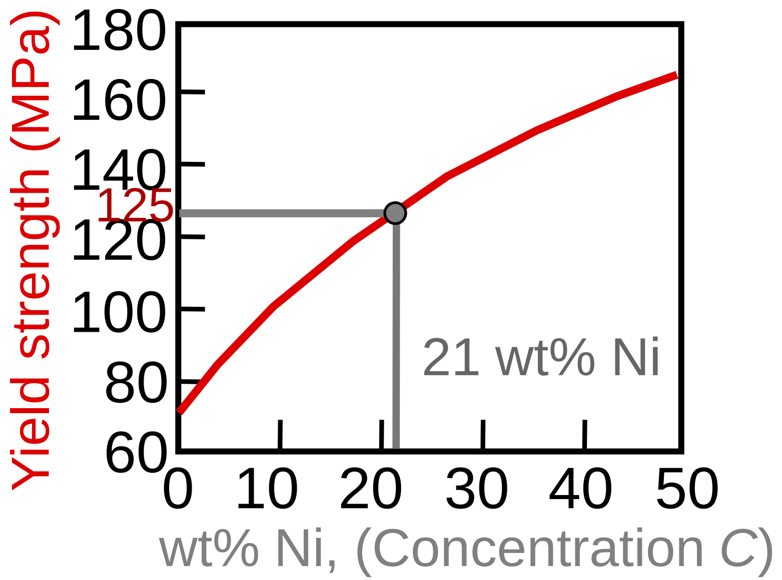
- Resistivity increases with:
  - -- temperature
  - -- wt% impurity
  - -- %*CW*

$$\rho = \rho_{thermal} + \rho_{impurity} + \rho_{deformation}$$

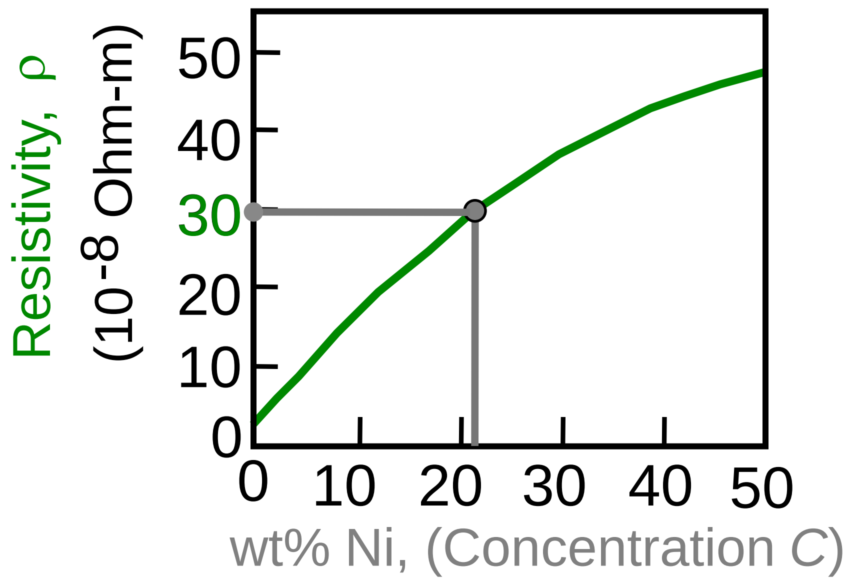
Estimating Conductivity

- Question:
  -- Estimate the electrical conductivity σ of a Cu-Ni alloy that has a yield strength of 125 MPa.

Adapted from Fig. 18.9, *Callister & Rethwisch 8e.*



Adapted from Fig. 7.16(b), *Callister & Rethwisch 8e.*



From step 1:

C_{Ni} = 21 wt% Ni

$$\rho = 30 \times 10^{-8} \mathrm{Ohm-m}$$

$$\sigma = \frac{1}{\rho} = 3.3 \times 10^{6} (\mathrm{Ohm-m})^{-1}$$

Drude's Classical Model of Metallic Conduction

Drude's Classical Model of Metals

(Beautifully explained in depth in Ashcroft and Mermin, Ch. 1)

- **Modern condensed matter physics** ***was BORN*** with ***the discovery of the electron*** by J.J. Thompson in 1897.
- Soon afterwards (1900) **Drude** used the new concept to postulate

A theory of metallic conductivity

Drude's Assumptions

1. Matter consists of light negatively charged electrons which are mobile, & heavy, static, positively charged ions.
2. The only interactions are electron-ion collisions, which take place in a very short time **t**.

- The neglect of the electron-electron interactions is

The Independent Electron Approximation.

- The neglect of the electron-ion Coulombic interactions is:

The Free Electron Approximation.

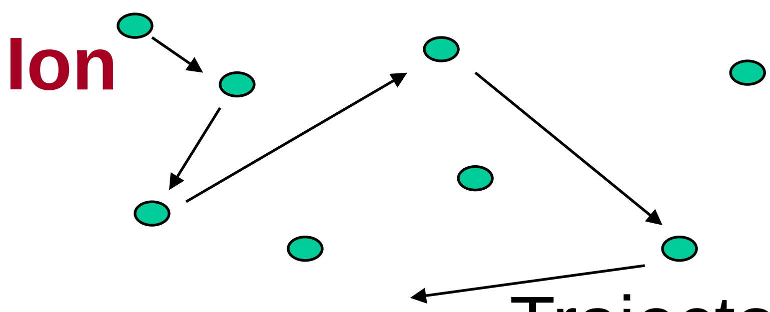
Drude's Assumptions Continued

3. Electron-ion collisions are assumed to dominate. These will abruptly alter the electron velocity & maintain thermal equilibrium.

4. The probability of an electron suffering a collision in a short time ***dt*** is ***dt/τ***, where

1/τ ≡ *The Electron Scattering Rate*.

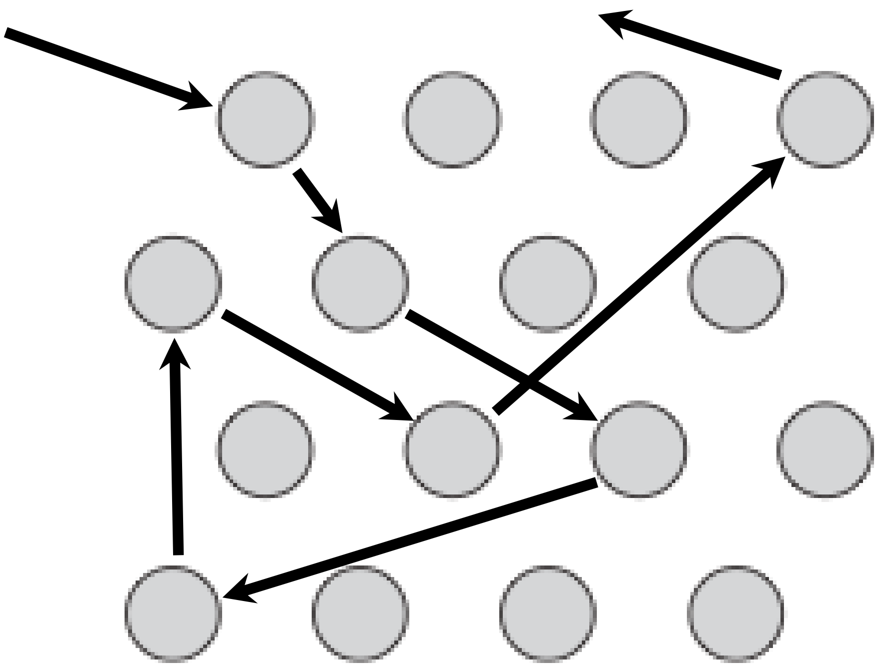
Electrons emerge from each collision with both the direction & magnitude of their velocity changed; the magnitude is changed due to the local temperature at the collision point. **1/τ** is often an adjustable parameter. See the figure.



The mean time between collisions is **τ.**

Trajectory of a **mobile electron**

Drude's classical theory



average rms speed

$$\frac{1}{2}mv_t^2 = \frac{3}{2}k_BT$$

$$v_t = \sqrt{\frac{3k_BT}{m}}$$

so at room temp.

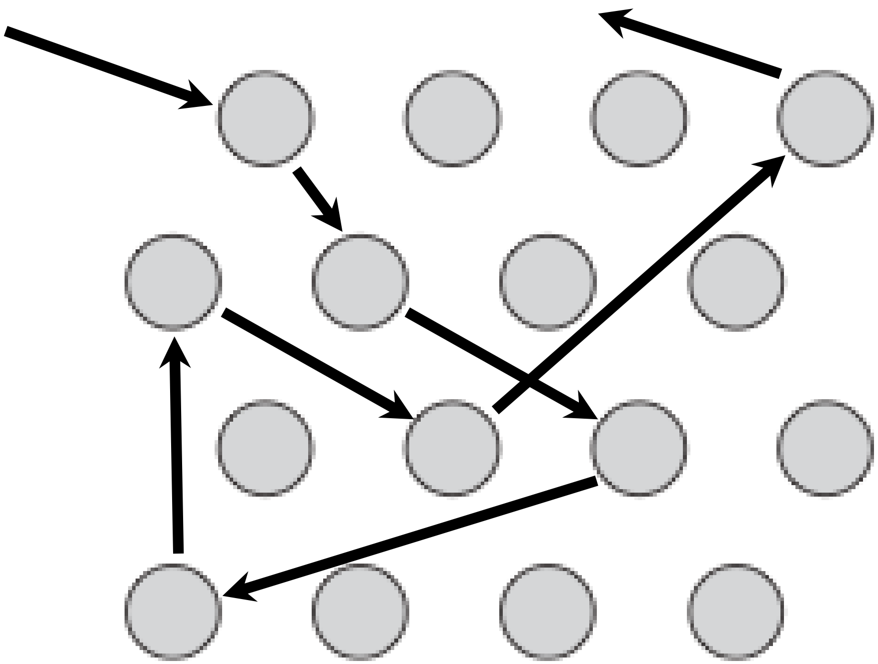
$$v_t \approx 10^5 \mathrm{ms}^{-1}$$

Drude's classical theory

relaxation time τ

(average time between scattering events)

mean free path $\lambda = \tau v_t$



$$\lambda \approx 1\mathrm{nm}$$
$$v_t \approx 10^5 \mathrm{ms}^{-1}$$
$$\tau \approx 1 \times 10^{-14}\ \mathrm{s}$$

Conduction electron Density *n*

#atoms
per
volume

calculate as $Z_V \rho_m / A$

#valence
electrons
per atom

density

atomic
mass

metal	Z_V	$n(10^{28}\ \mathrm{m}^{-3})$
Li	1	4.7
Na	1	2.65
K	1	1.4
Rb	1	1.15
Cs	1	0.91
Cu	1	8.47
Ag	1	5.86
Au	1	5.9
Be	2	24.7
Mg	2	8.61
Ba	2	3.15
Fe	2	17
Al	3	18.1
Pb	4	13.2
Sb	5	16.5
Bi	5	14.1

Drude theory: electrical conductivity

we apply an electric field. The equation of motion is

$$m_e \frac{d\mathbf{v}}{dt} = -e\boldsymbol{\mathcal{E}}$$

integration gives

$$\mathbf{v}(t) = \frac{-e\boldsymbol{\mathcal{E}}t}{m_e}$$

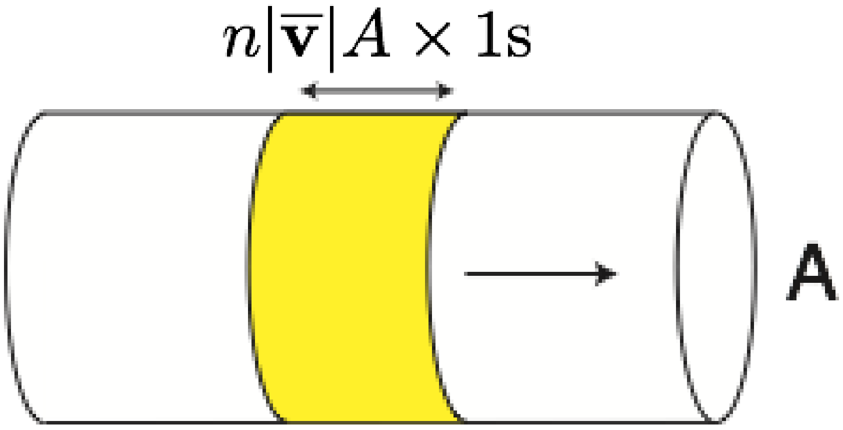
and if τ is the average time between collisions then the average drift speed is

$$\overline{\mathbf{v}} = \frac{-e\boldsymbol{\mathcal{E}}\tau}{m_e}$$

for $\mathcal{E} \approx 10\mathrm{Vm}^{-1}$ we get $\overline{v} = 10^{-2}\mathrm{ms}^{-1}$

remember: $v_t = 10^5\mathrm{ms}^{-1}$

Drude theory: electrical conductivity



number of electrons passing in unit time

$$n|\bar{\mathbf{v}}|A$$

current of negatively charged electrons

$$-en|\bar{\mathbf{v}}|A$$

current density

$$\mathbf{j} = n\bar{\mathbf{v}}(-e)$$

and with $\bar{\mathbf{v}} = \dfrac{-e\mathcal{E}\tau}{m_e}$ we get

Ohm's law

$$\mathbf{j} = \frac{ne^2\tau}{m_e}\mathcal{E}$$

Drude theory: electrical conductivity

Ohm's law

$$\mathbf{j} = \frac{ne^2\tau}{m_e}\boldsymbol{\mathcal{E}}$$

$$\mathbf{j} = \sigma\boldsymbol{\mathcal{E}} = \frac{\boldsymbol{\mathcal{E}}}{\rho}$$

and we can define the conductivity

$$\sigma = \frac{ne^2\tau}{m_e} = n\mu e$$

and the resistivity

$$\rho = \frac{m_e}{ne^2\tau} = \frac{1}{n\mu e}$$

and the mobility

$$\mu = \frac{e\tau}{m_e}$$

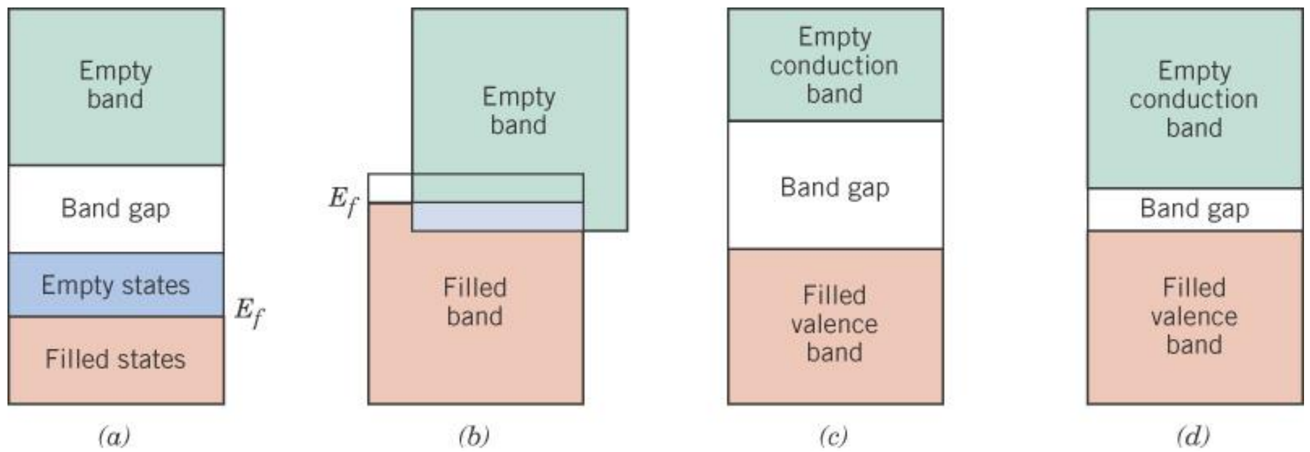
$$|\mathbf{v}| = \mu|\boldsymbol{\mathcal{E}}|$$

II. SEMICONDUCTIVITY

Conductivity of semiconducting materials is lower than from metals
Sensitive to minute concentrations of impurities
Intrinsic: pure material
Extrinsic: doped with impurity atoms

12.10 Intrinsic Semiconduction

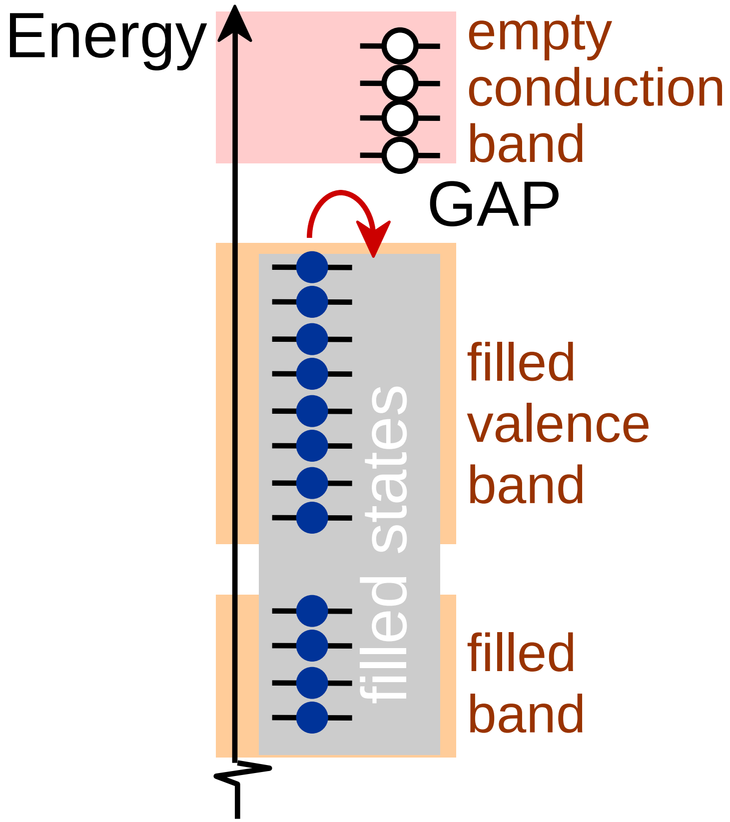
Band structure
Si (1.1 eV)
Ge (0.7 eV)
GaAs (IIIA-VA)
InSb (IIIA-VA)
CdS (IIB-VIA)
ZnTe (IIB-VIA)



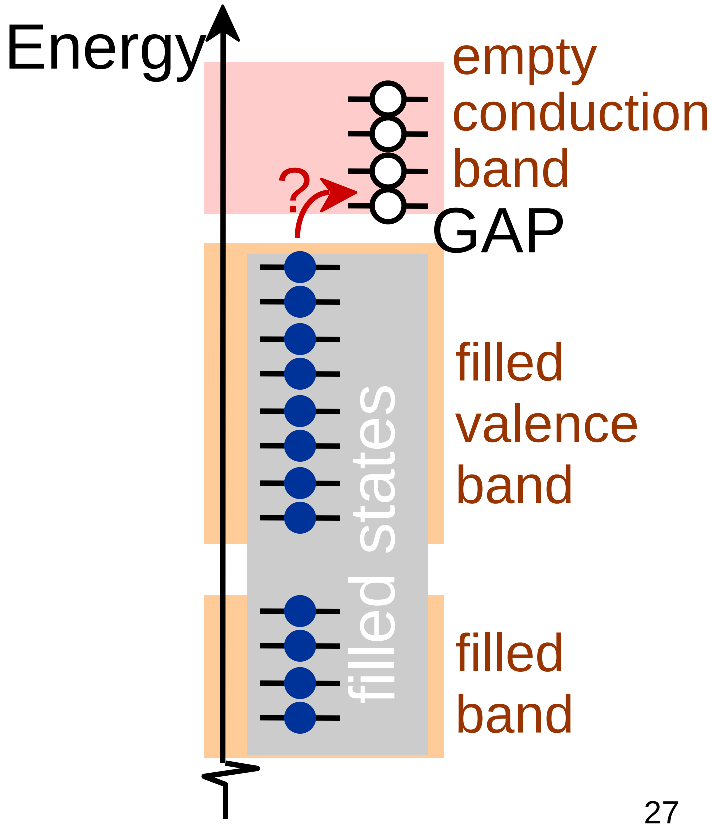
We have electrons as carriers in metals and “electrons” and ‘holes’ as carriers in semiconductors

Energy Band Structures: Insulators & Semiconductors

- Insulators:
  -- wide band gap (> 2 eV)
  -- few electrons excited
  across band gap

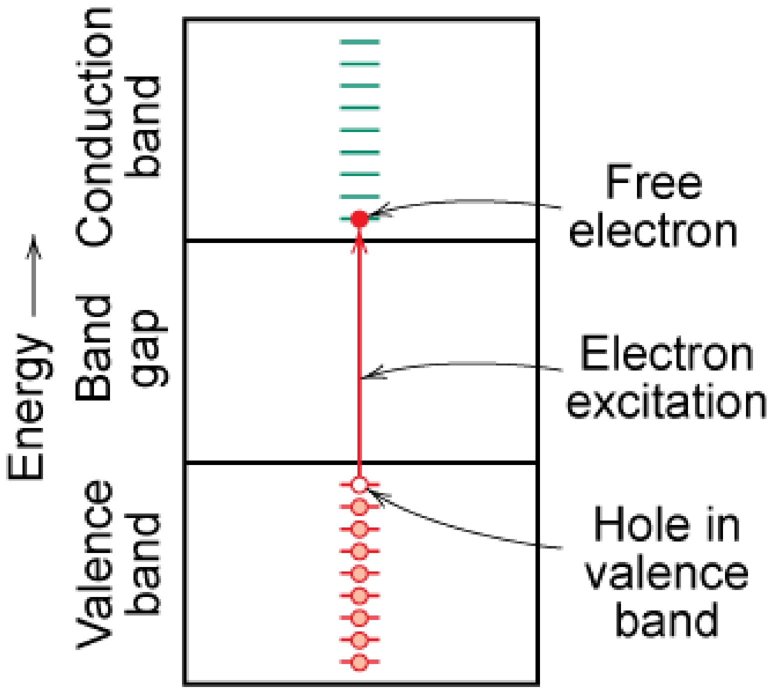


- Semiconductors:
  -- narrow band gap (< 2 eV)
  -- more electrons excited
  across band gap



Charge Carriers in Insulators and Semiconductors

Adapted from Fig. 18.6(b), *Callister & Rethwisch 8e.*



Two types of electronic charge carriers:

Free Electron

- negative charge
- in conduction band

Hole

- positive charge
- vacant electron state in the valence band

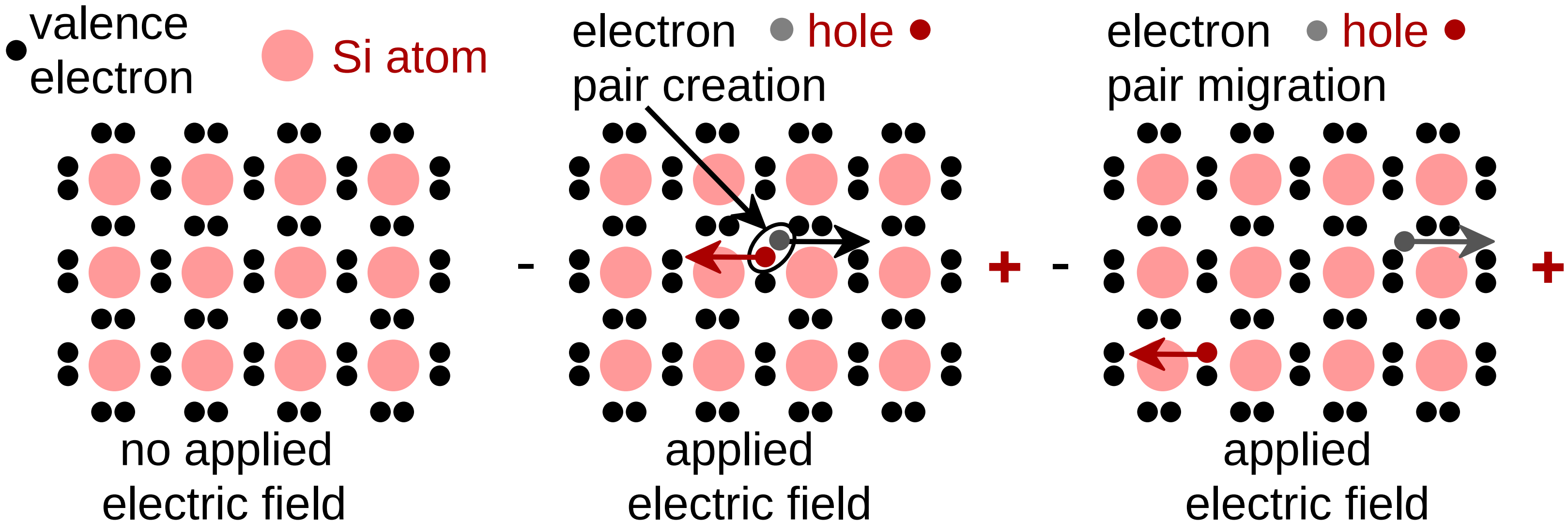
Move at different speeds - drift velocities

Intrinsic Semiconductors

- Pure material semiconductors: e.g., silicon & germanium
  – Group IVA materials
- Compound semiconductors
  – III-V compounds
    - Ex: GaAs & InSb
  – II-VI compounds
    - Ex: CdS & ZnTe
  – The wider the electronegativity difference between the elements the wider the energy gap.

Intrinsic Semiconduction in Terms of Electron and Hole Migration

- Concept of electrons and holes:



Adapted from Fig. 18.11, *Callister & Rethwisch 8e.*

- Electrical Conductivity given by:

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

holes/m^3

hole mobility

electrons/m^3

electron mobility

Number of Charge Carriers

Intrinsic Conductivity

$$\boxed{\sigma = n|e|\mu_e + p|e|\mu_h}$$

- for intrinsic semiconductor $n = p = n_i$

$$\therefore \qquad \sigma = n_i|e|(\mu_e + \mu_h)$$

- Ex: GaAs

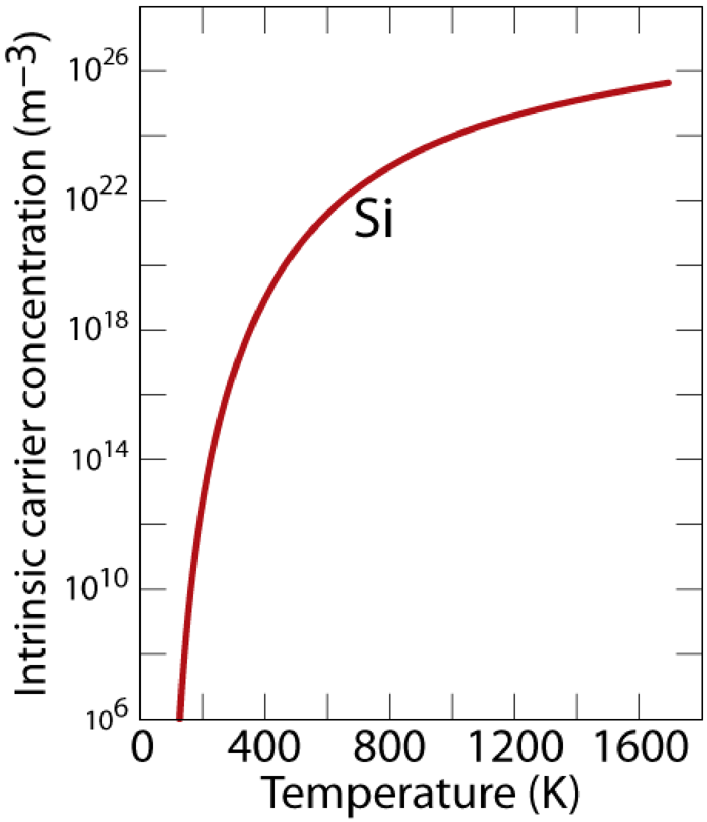
$$n_i = \frac{\sigma}{|e|(\mu_e + \mu_h)} = \frac{10^{-6}(\Omega \cdot \mathrm{m})^{-1}}{(1.6\mathrm{x}10^{-19}\,\mathrm{C})(0.85 + 0.45\,\mathrm{m^2/V \cdot s})}$$

For GaAs $\quad n_i = 4.8 \times 10^{24}\ \mathrm{m}^{-3}$

For Si $\quad n_i = 1.3 \times 10^{16}\ \mathrm{m}^{-3}$

Intrinsic Semiconductors: Conductivity vs *T*

- Data for Pure Silicon:
  - -- σ increases with *T*
  - -- opposite to metals



Adapted from Fig. 18.16,
Callister & Rethwisch 8e.

$$\sigma = n_i |e| (\mu_e + \mu_h)$$

$$n_i \propto e^{-E_{gap}/kT}$$

material	band gap (eV)
Si	1.11
Ge	0.67
GaP	2.25
CdS	2.40

Selected values from Table 18.3,
Callister & Rethwisch 8e.

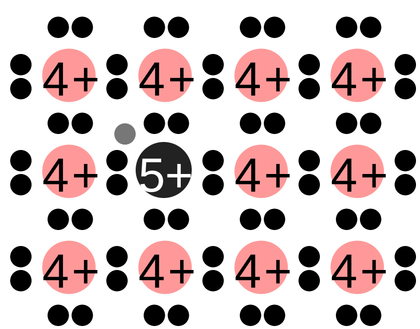
Intrinsic vs Extrinsic Conduction

- Intrinsic:
  - -- case for pure Si
  - -- # electrons = # holes ($n = p$)
- Extrinsic:
  - -- electrical behavior is determined by presence of impurities that introduce excess electrons or holes
  - -- $n \neq p$

- n-type Extrinsic: ($n >> p$)
- p-type Extrinsic: ($p >> n$)

Phosphorus atom

$\sigma \approx n|e|\mu_e$



no applied electric field

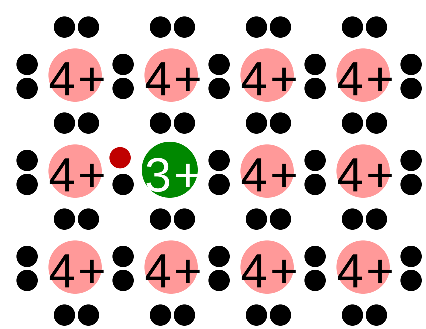
hole

conduction electron

valence electron

Si atom

Boron atom

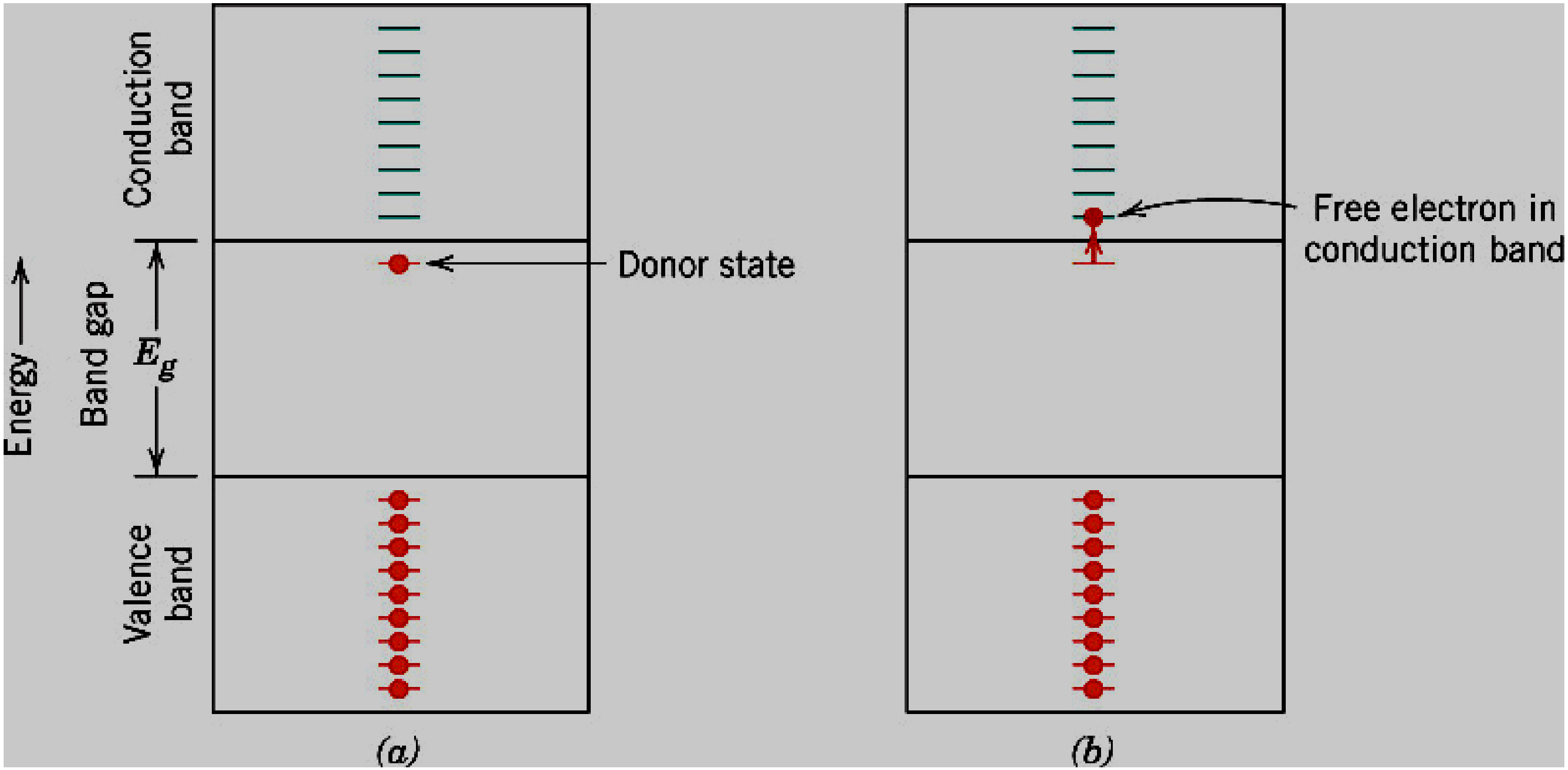


no applied electric field

$\sigma \approx p|e|\mu_h$

Adapted from Figs. 18.12(a) & 18.14(a), *Callister & Rethwisch 8e.*

n-type extrinsic semiconductor



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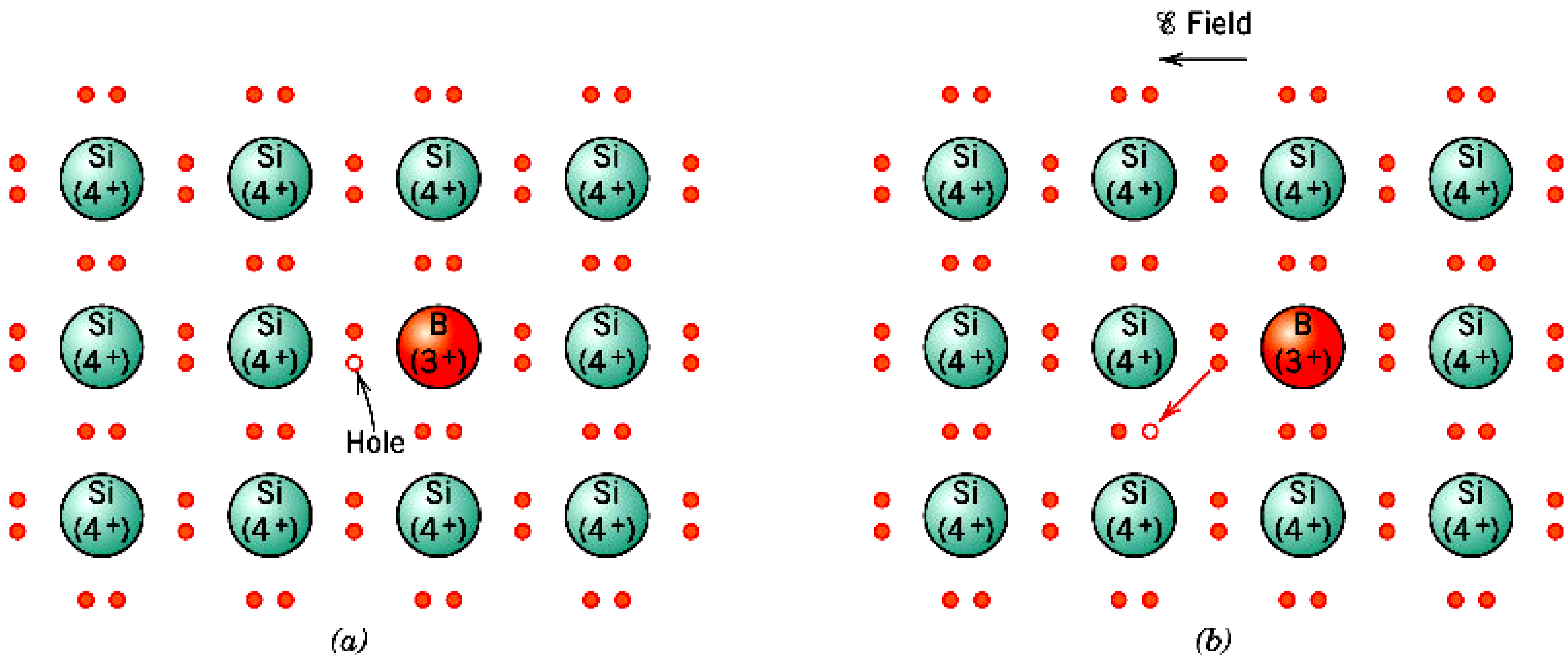
$$\sigma \approx n|e|\mu_e$$

p-type extrinsic semiconductor



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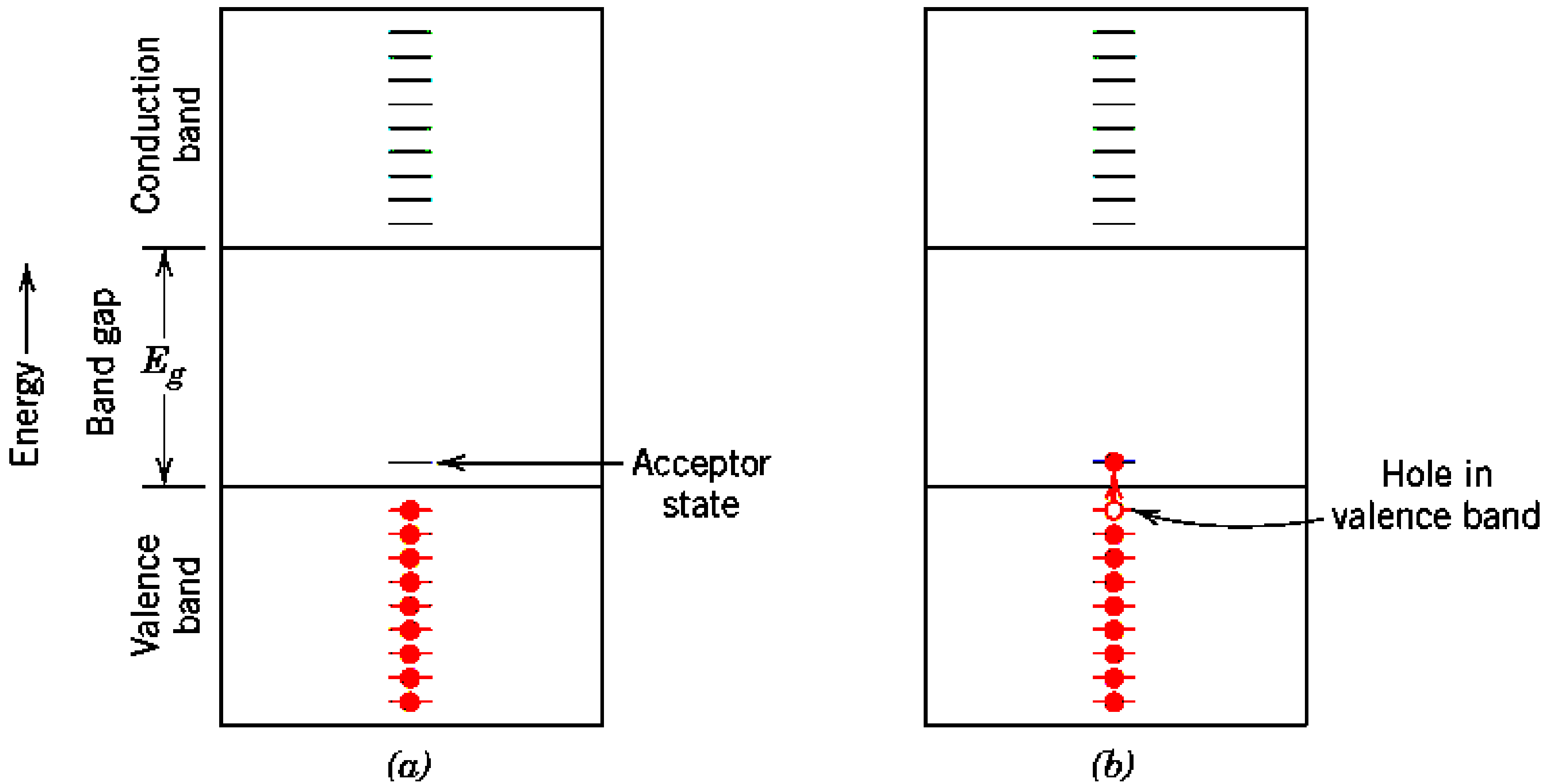
$$\sigma \approx p|e|\mu_h$$

p-type extrinsic semiconductor



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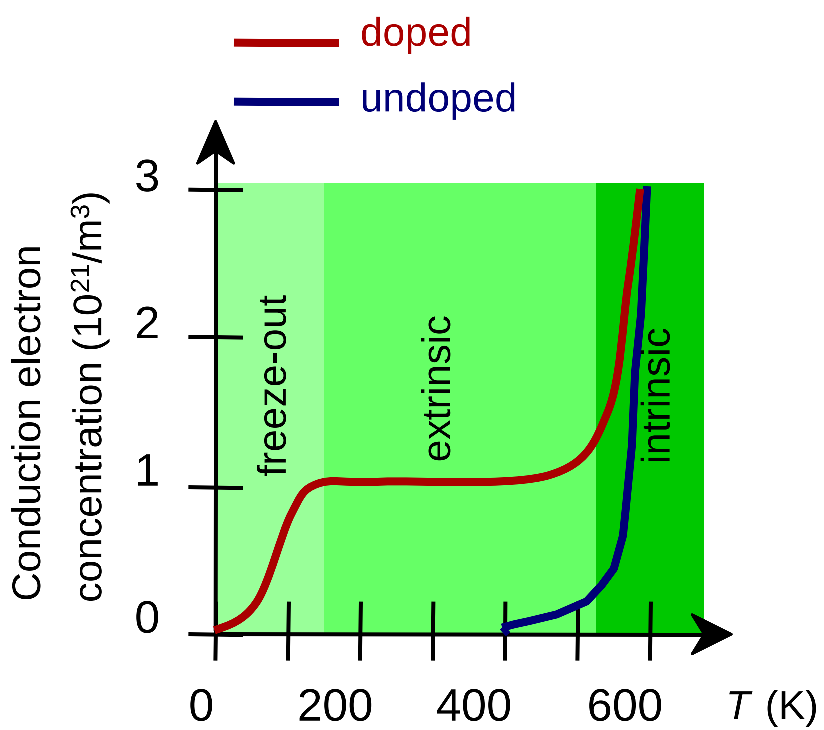
Extrinsic Semiconductors: Conductivity vs. Temperature

- Data for Doped Silicon:
  - -- σ increases doping
  - -- reason: imperfection sites lower the activation energy to produce mobile electrons.

- Comparison: intrinsic vs extrinsic conduction...
  - -- extrinsic doping level: $10^{21}/m^3$ of a *n*-type donor impurity (such as P).
  - -- for T < 100 K: "freeze-out", thermal energy insufficient to excite electrons.
  - -- for 150 K < T < 450 K: "extrinsic"
  - -- for T >> 450 K: "intrinsic"



Adapted from Fig. 18.17, *Callister & Rethwisch 8e.* (Fig. 18.17 from S.M. Sze, *Semiconductor Devices, Physics, and Technology*, Bell Telephone Laboratories, Inc., 1985.)

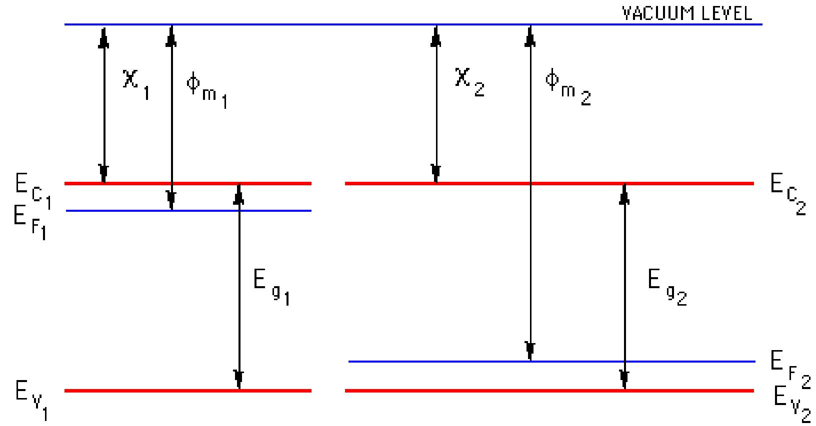
p-n junctions

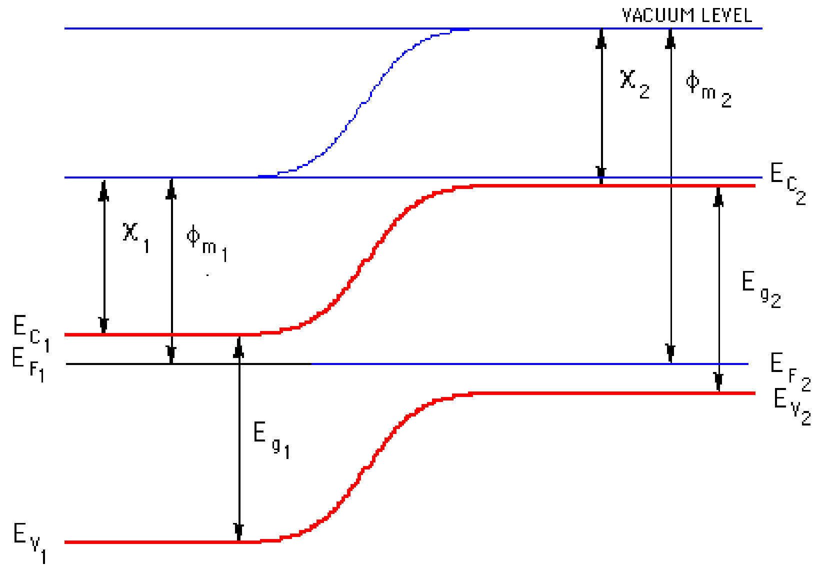
pn **Junction Si solar cells at work. Honda's two seated Dream car is powered by photovoltaics. The Honda Dream was first to finish 3,010 km in four days in the 1996 World Solar Challenge.**

|SOURCE: Courtesy of Centre for Photovoltaic Engineering, University of New South Wales, Sydney, Australia.

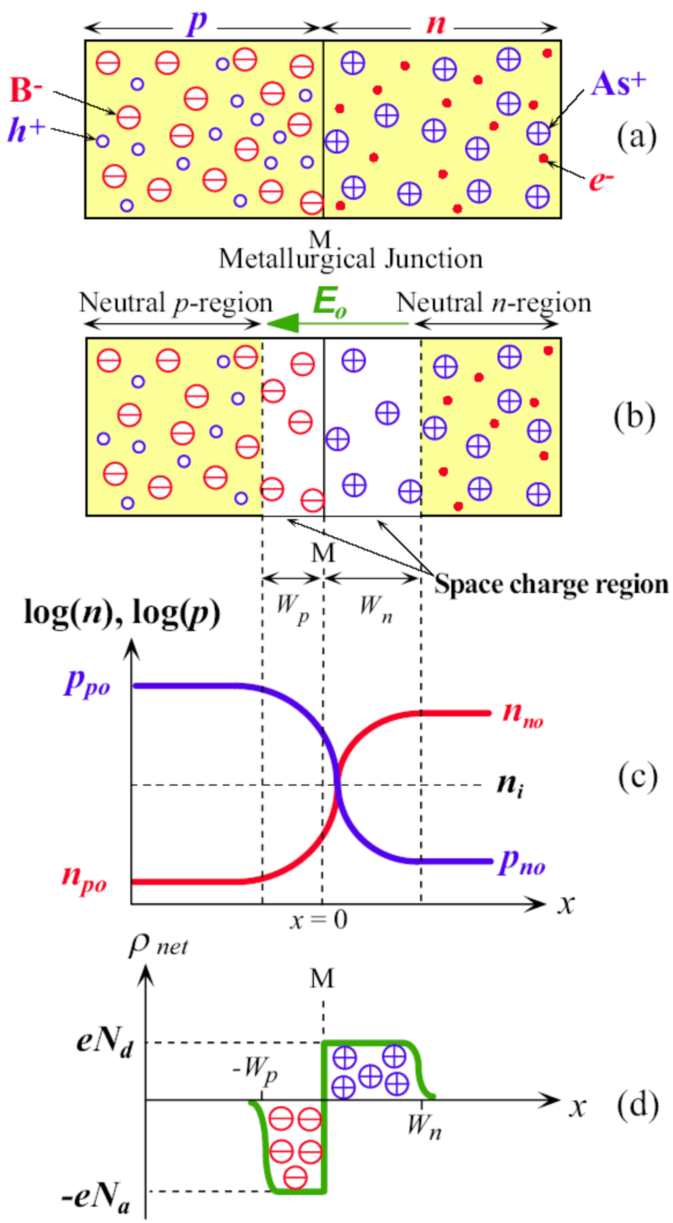
Semiconductor Homojunctions

An ideal n-p homojunction





From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)



Properties of the pn junction

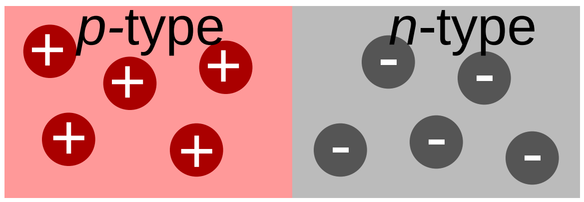
Fig 6.1

From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill,

p-n Rectifying Junction

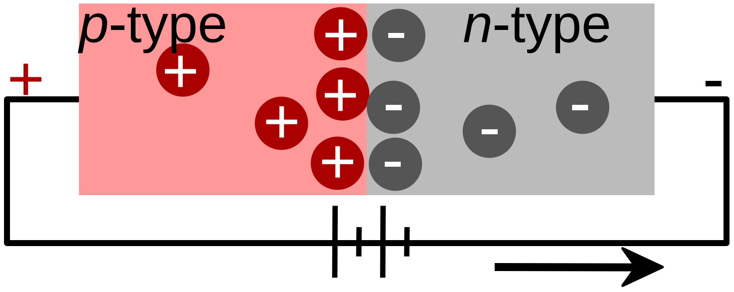
- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current).
- Processing: diffuse P into one side of a B-doped crystal.

-- No applied potential: no net current flow.

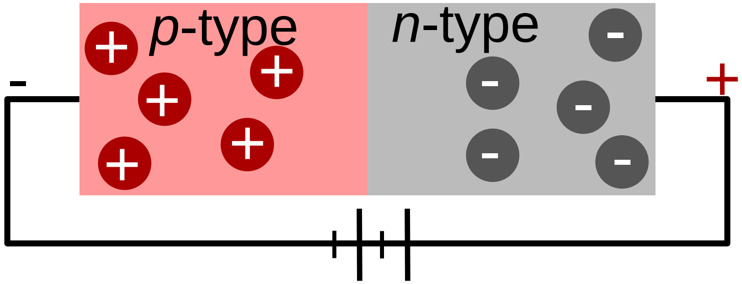


Adapted from Fig. 18.21 Callister & *Rethwisch 8e.*

-- Forward bias: carriers flow through *p*-type and *n*-type regions; holes and electrons recombine at *p-n* junction; current flows.



-- Reverse bias: carriers flow away from *p-n* junction; junction region depleted of carriers; little current flow.



Properties of Rectifying Junction

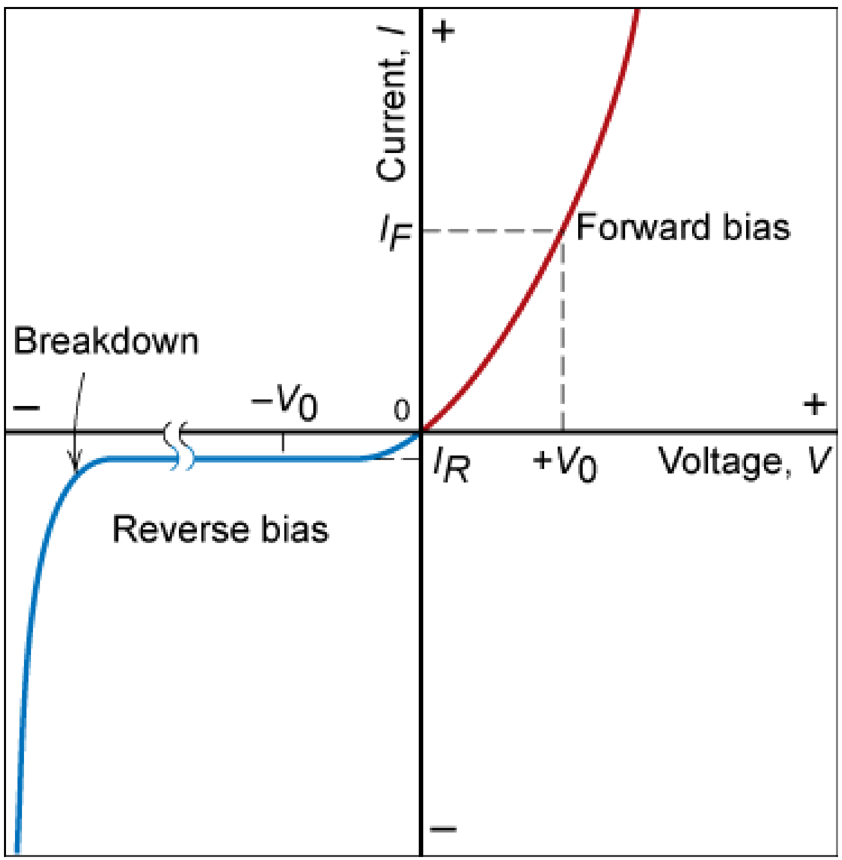


Fig. 18.22, *Callister & Rethwisch 8e.*

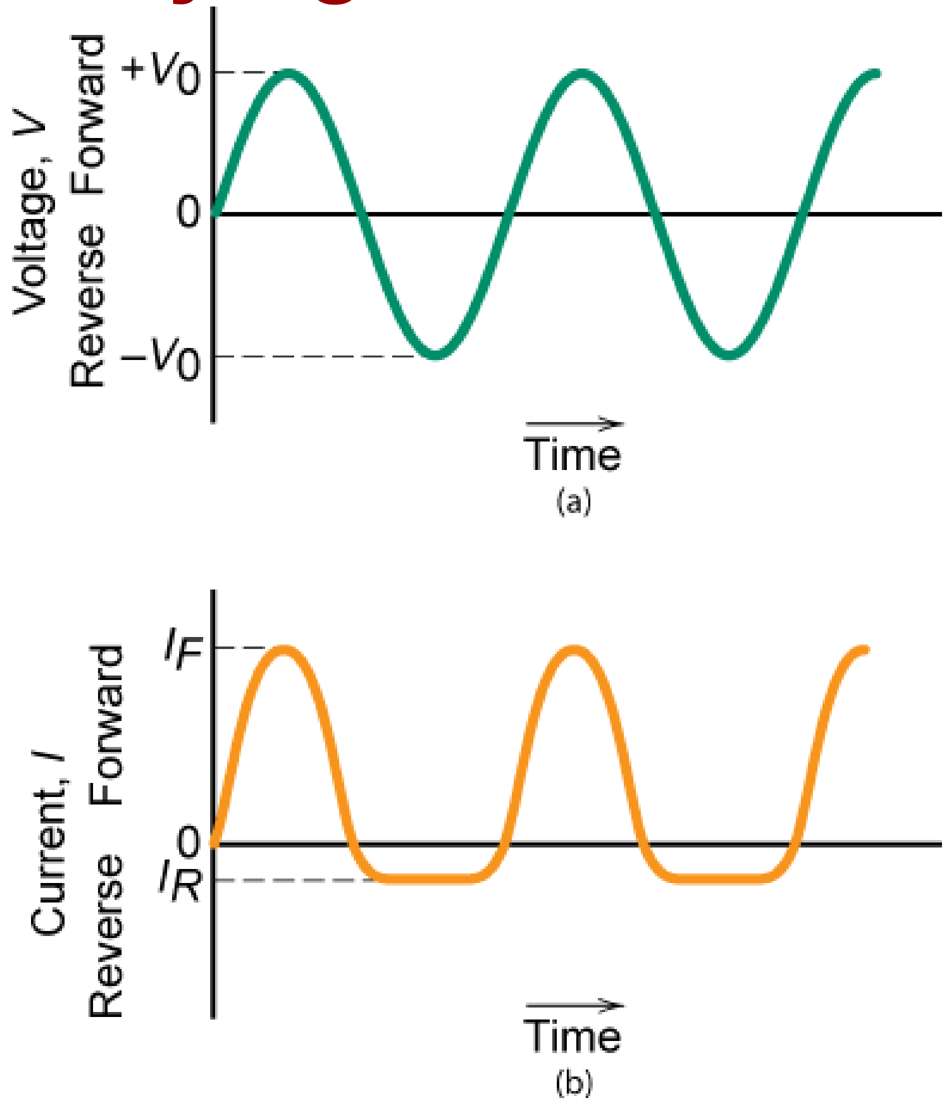


Fig. 18.23, *Callister & Rethwisch 8e.*

MOSFET Transistor Integrated Circuit Device

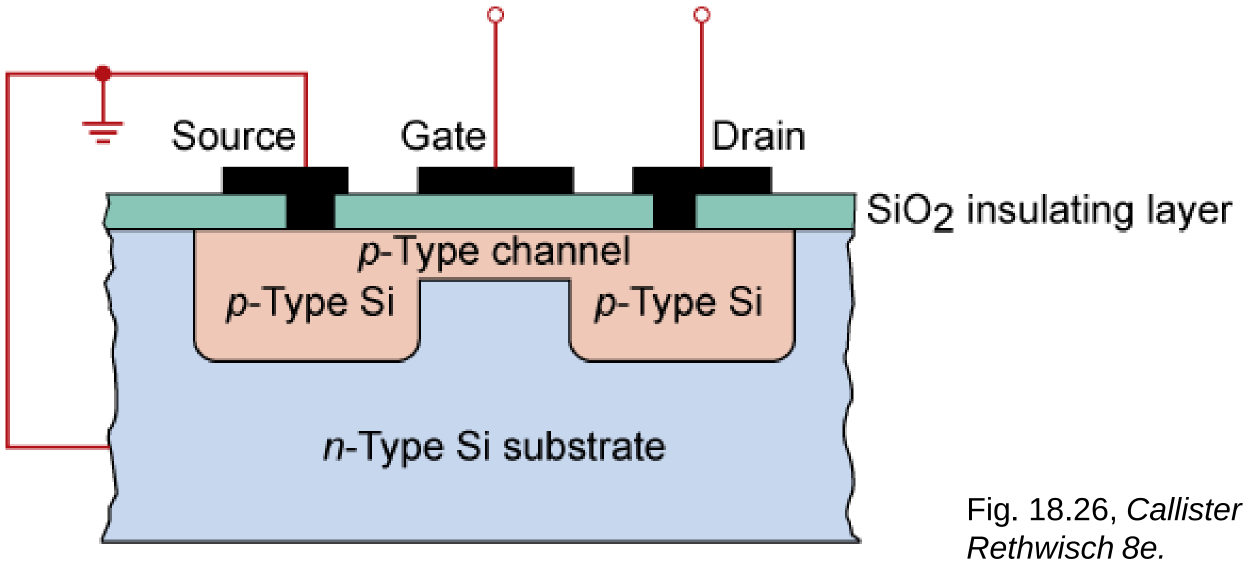


Fig. 18.26, *Callister & Rethwisch 8e.*

- MOSFET (metal oxide semiconductor field effect transistor)
- Integrated circuits - state of the art ca. 50 nm line width
  - ~ 1,000,000,000 components on chip
  - chips formed one layer at a time

Dielectrics

Capacitors and Optics

Dielectric Behavior

Dielectric material

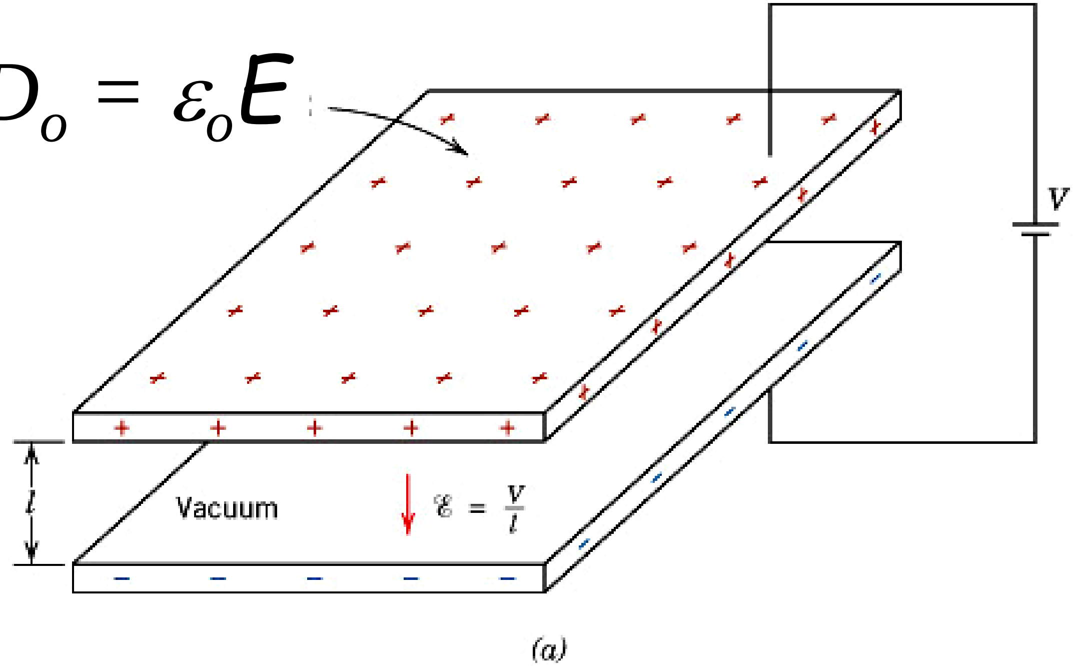
Electric dipole structure

Charge separation

$$C = \frac{Q}{V} \qquad C = \varepsilon_o \frac{A}{l}$$

ε_o = permittivity of vacuum
= $8.85\text{x}10^{-12}$ F/m

$$D_o = \varepsilon_o E$$



$$D_o = \varepsilon_o E + P$$

$$C = \varepsilon \frac{A}{l}$$

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o}$$

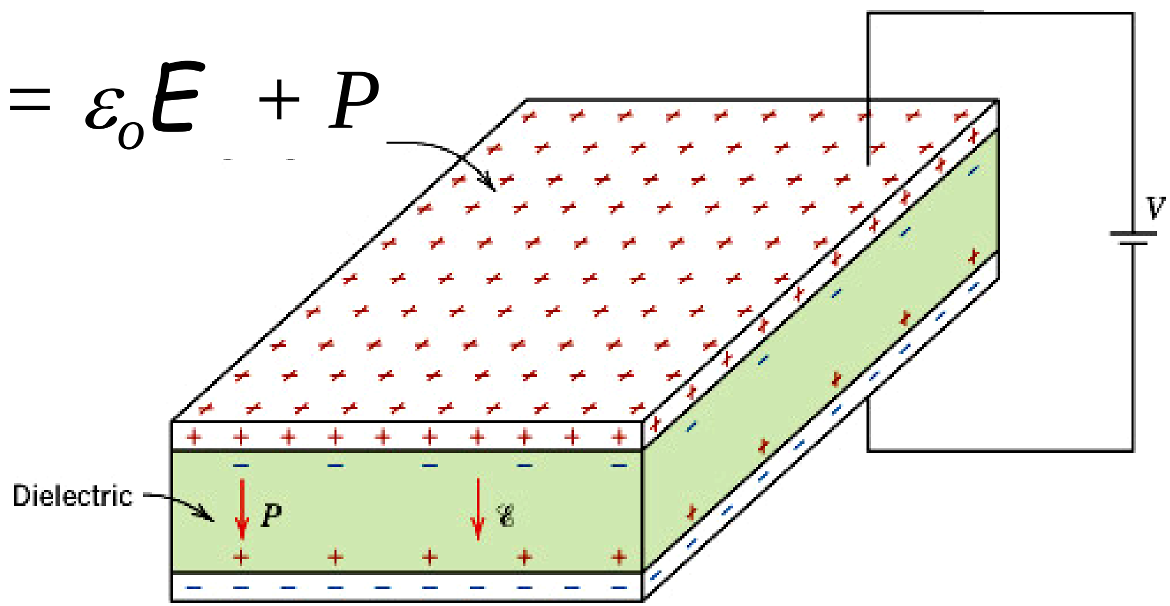


Table 12.5 Dielectric Constants and Strengths for Some Dielectric Materials

Material	*Dielectric Constant* 60 Hz	*Dielectric Constant* 1 MHz	*Dielectric Strength (V/mil)*[a]
		Ceramics	
Titanate ceramics	—	15–10,000	50–300
Mica	—	5.4–8.7	1000–2000
Steatite (MgO–SiO_2)	—	5.5–7.5	200–350
Soda–lime glass	6.9	6.9	250
Porcelain	6.0	6.0	40–400
Fused silica	4.0	3.8	250
		Polymers	
Phenol-formaldehyde	5.3	4.8	300–400
Nylon 6,6	4.0	3.6	400
Polystyrene	2.6	2.6	500–700
Polyethylene	2.3	2.3	450–500
Polytetrafluoroethylene	2.1	2.1	400–500

[a] One mil = 0.001 in. These values of dielectric strength are average ones, the magnitude being dependent on specimen thickness and geometry, as well as the rate of application and duration of the applied electric field.

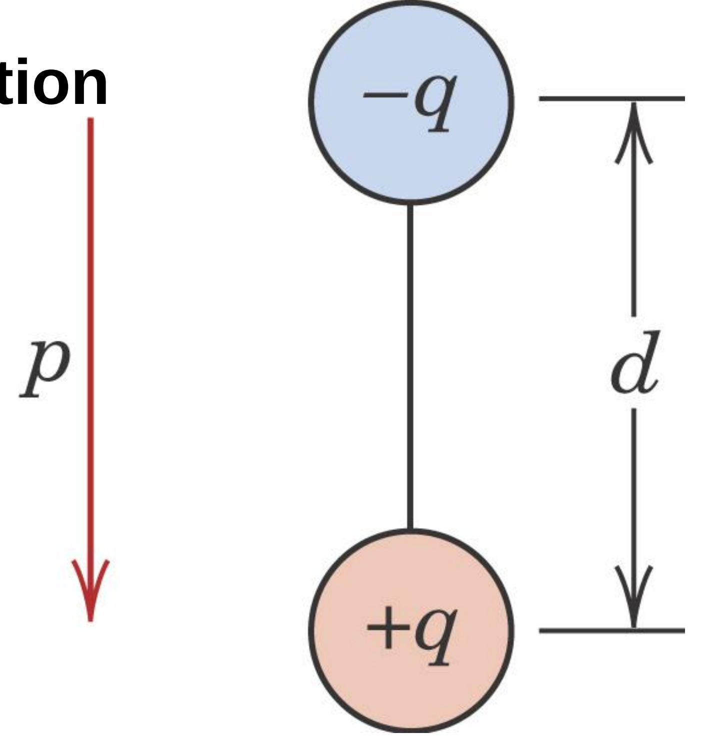
c12tf05

12.22 Dielectric Strength

Substance	Dielectric Strength (MV/m)
Air	3
Quartz	8
Strontium titanate	8
Neoprene rubber	12
Nylon	14
Pyrex glass	14
Silicone oil	15
Paper	16
Bakelite	24
Polystyrene	24
Teflon	60

12.19 Field vectors and polarization

$$p = qd$$

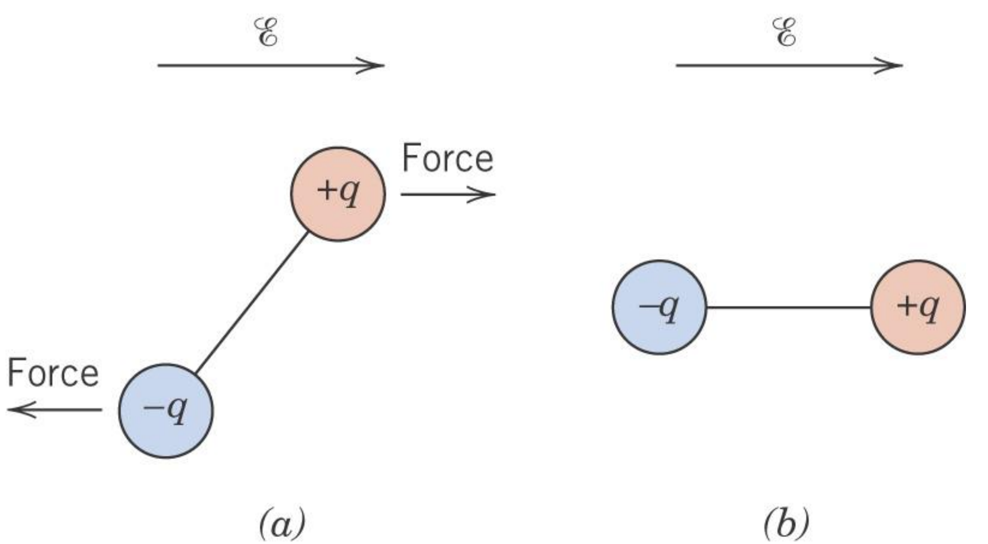


Surface charge density or dielectric displacement (C/m^2)

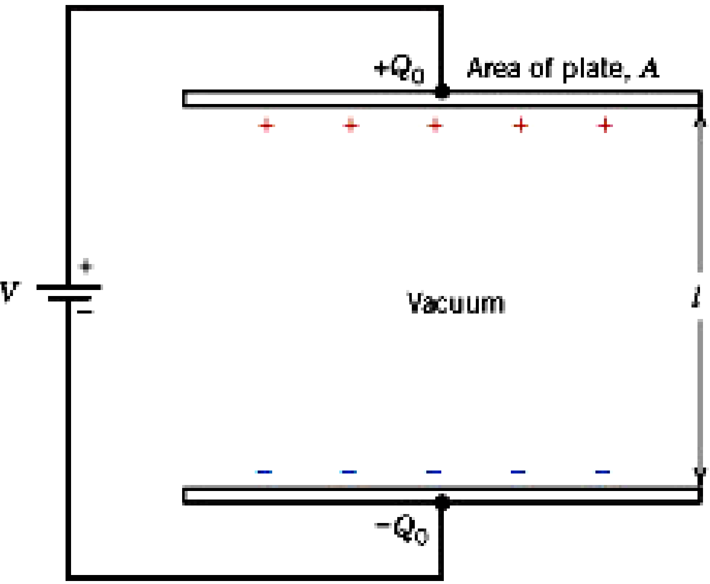
$$D_o = \varepsilon_o \mathsf{E}$$

For the dielectric case

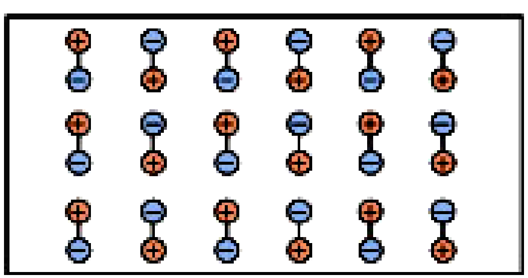
$$D = \varepsilon \mathsf{E}$$



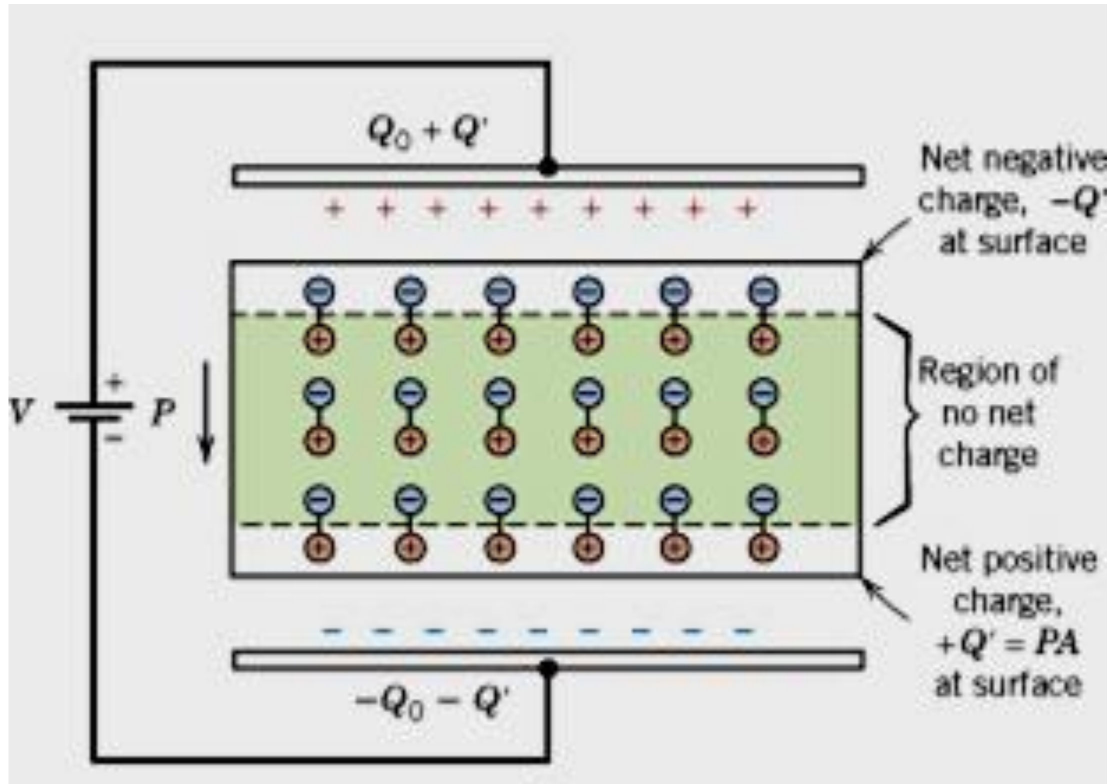
$D_o = \varepsilon_o E + P$ where P is the polarization (C/m^2) or total dipole moment per unit of volume of the dielectric



(a)

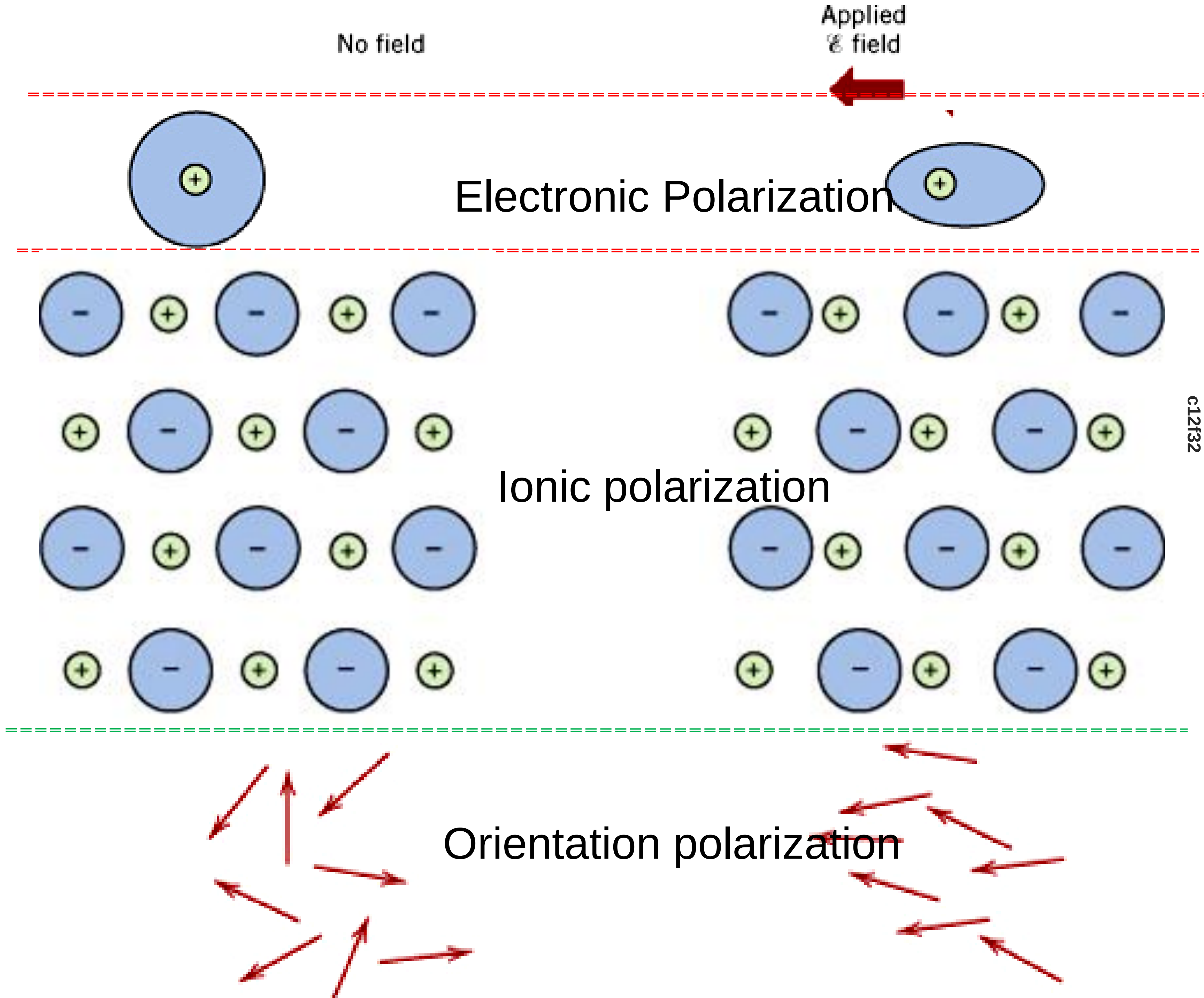


(b)



(c)

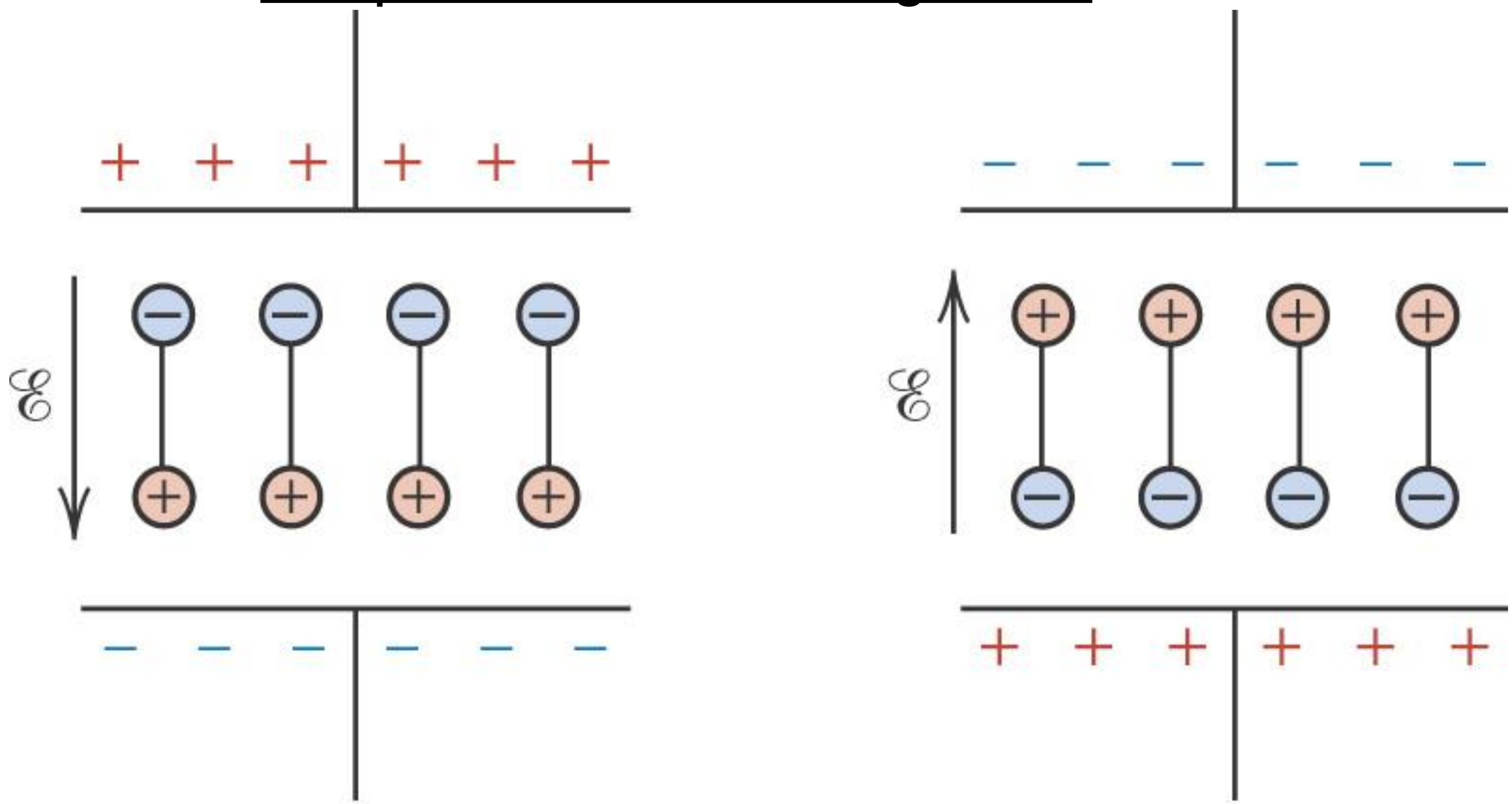
$$P = \varepsilon_o(\varepsilon_r - 1)E$$



No field
Applied
ℰ field
Electronic Polarization
Ionic polarization
Orientation polarization
c12f32

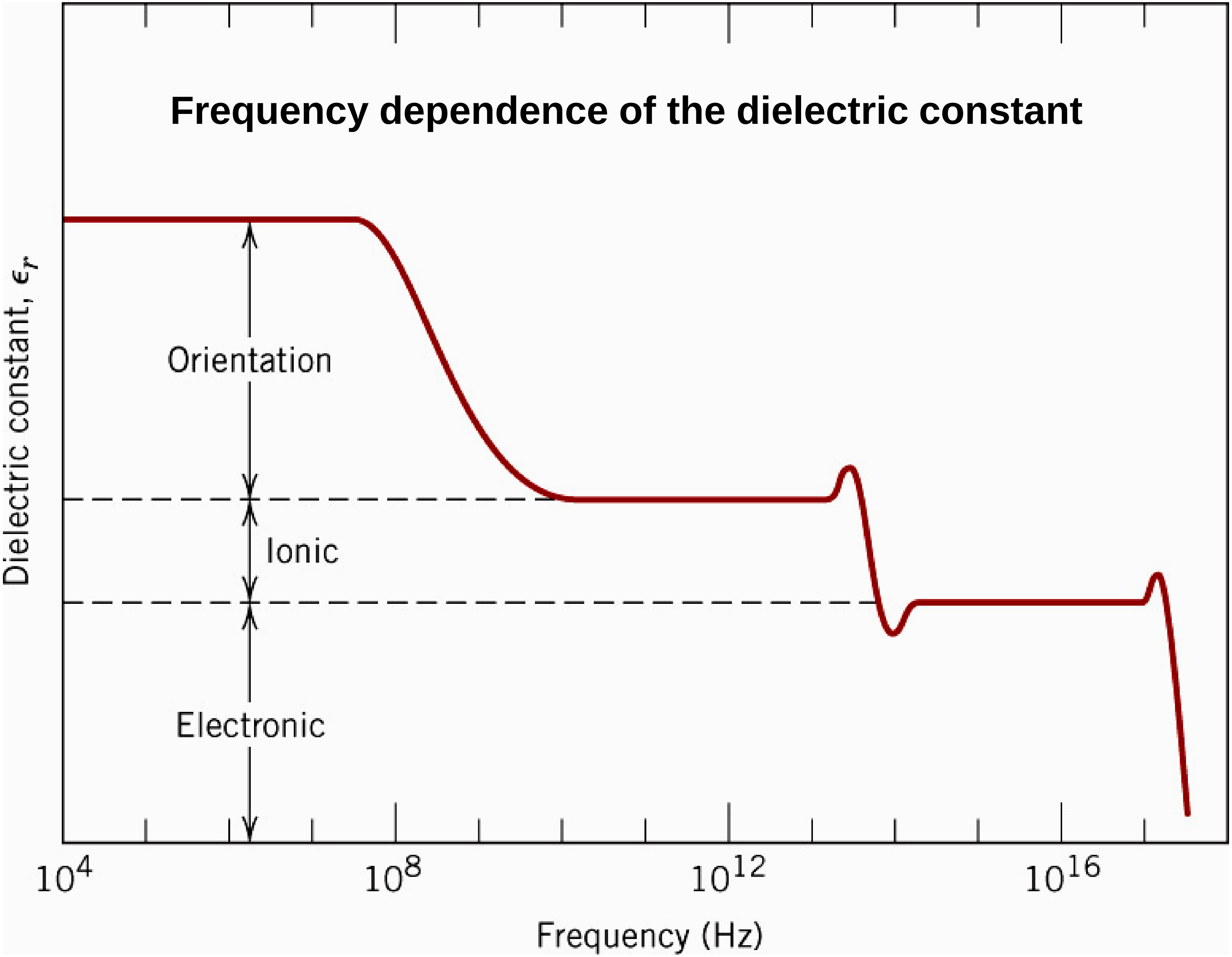
12.21 Frequency Dependence of the dielectric constant

Response to alternating fields



Reorientation time --- relaxation frequency

Frequency dependence of the dielectric constant



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Types of Polarizations and Frequency Range

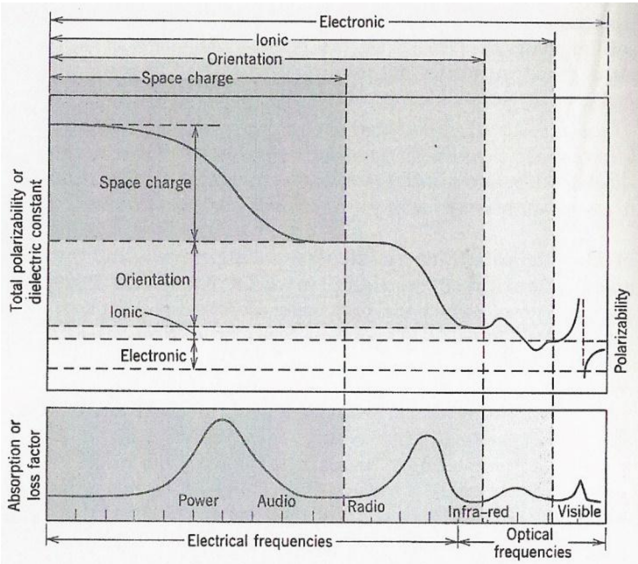
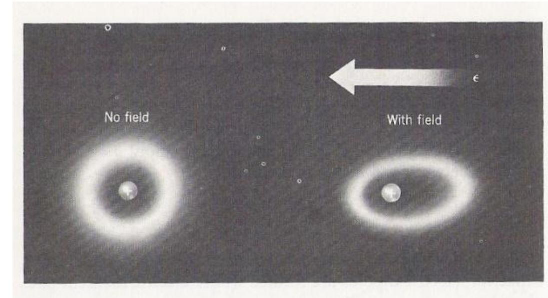
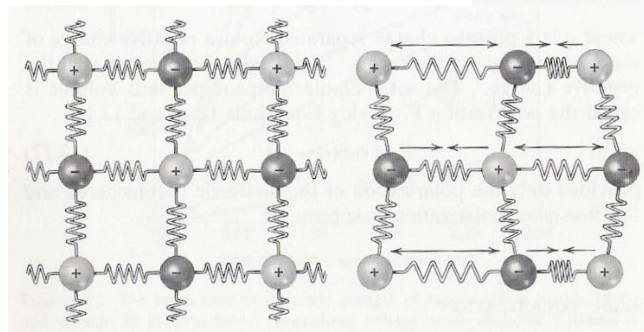


Figure 12.5 Variation of the total polarizability and dielectric absorption as a function of frequency. Each contribution to the polarizability decays as its characteristic resonant frequency is exceeded. (After E. J. Murphy and S. D. Morgan, *Bell System Tech. Jl.*, 16, 493, 1937.)

Electronic polarization: Visible Optical spectrum

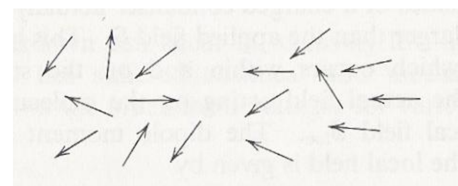


: charge cloud around the nucleus is distorted by the field



Ionic polarization: low optical and infra-red spectrum

Directional polarization: low infra-red spectrum



Orientation polarization

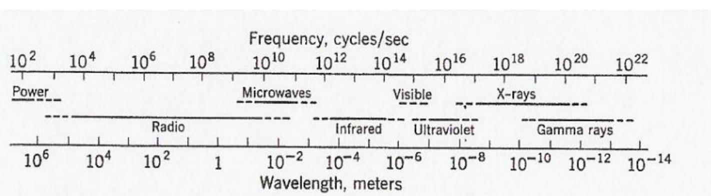
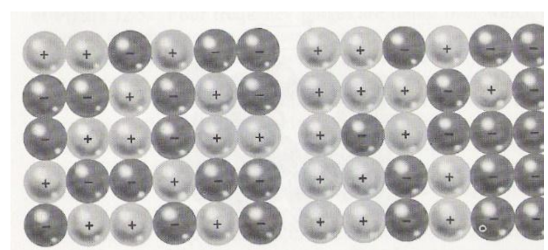


Figure 13.1 The electromagnetic spectrum, on a logarithmic scale.



Space charge polarization

Space polarization: Audio and Power frequencies

Dielectric Breakdown

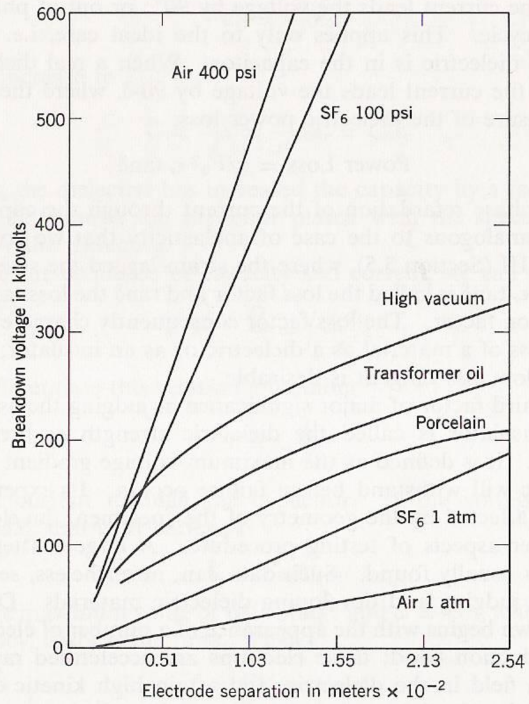


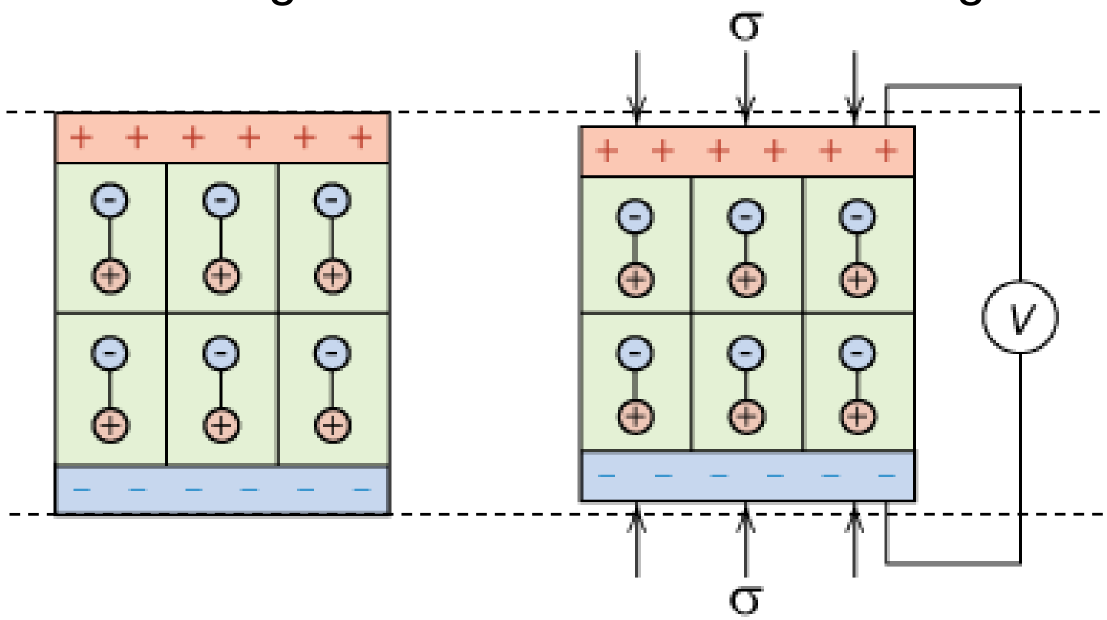
Figure 12.2 D-c breakdown or dielectric strength of various solids, liquids, gases and vacuum, in uniform fields. Breakdown voltage versus dielectric thickness i plotted. (From J. Trump, in A. von Hippel, *Dielectric Materials and Applications* Wiley, New York, 1954.)

Piezoelectric Materials

Piezoelectricity

– application of stress induces voltage

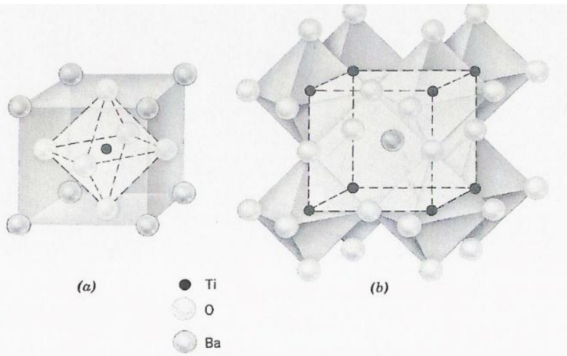
– application of voltage induces dimensional change



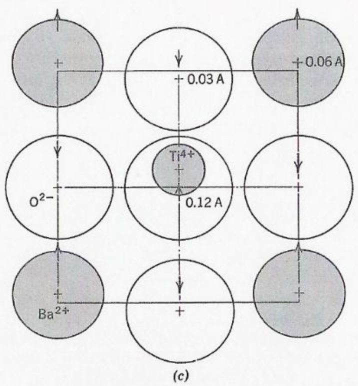
stress-free with applied stress

Adapted from Fig. 18.36, *Callister & Rethwisch 8e.* (Fig. 18.36 from Van Vlack, Lawrence H., Elements of Materials Science and Engineering, 1989, p.482, Adapted by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)

Piezoelectrics



Ion positions in ideal perovskite structure, i.e., $BaTiO_3$ above the Curie temperature



Top view of unit cell (*a*), showing the shifting of the ions below the Curie temperature

Figure 12.9 Crystal structure and ferroelectricity in barium titanate.

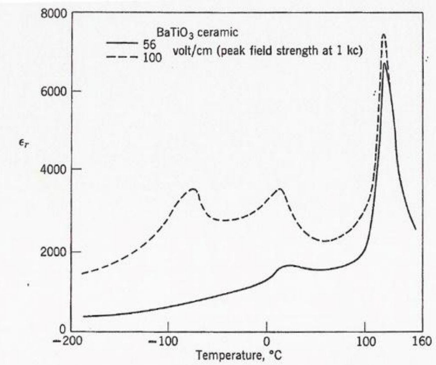


Figure 12.10 Permittivity of barium titanate ceramic as function of temperature. (Measurements of W. B. Westphal, Laboratory for Insulation Research, Massachusetts Institute of Technology.)

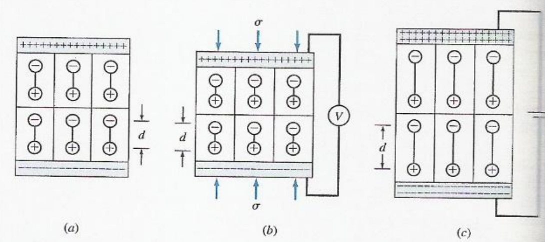
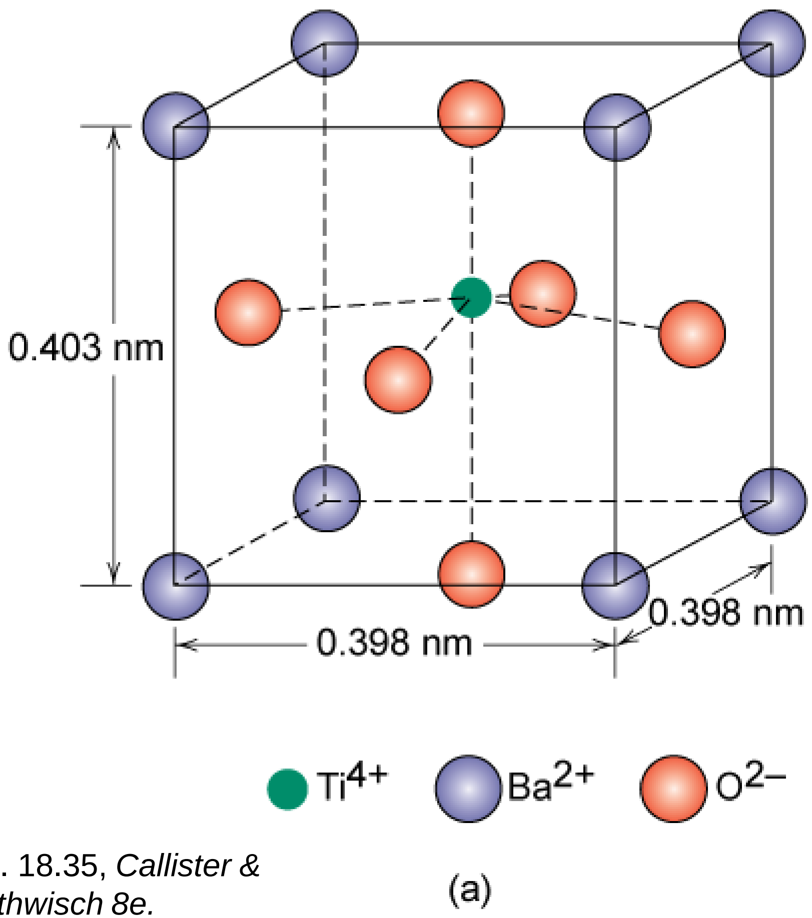


Figure 10.42
(*a*) Schematic illustration of electric dipoles within a piezoelectric material.
(*b*) Compressive stresses on material cause a voltage difference to develop due to change in electric dipoles. (*c*) Applied voltage across ends of sample causes dimensional change and changes the electric dipole moment.
(After L. H. Van Vlack, "Elements of Materials Science and Engineering," 4th ed., Addison-Wesley, 1980, Fig. 8-6.3, p. 305.)

Ferroelectric Ceramics

- Experience spontaneous polarization



$BaTiO_3$ -- ferroelectric below its Curie temperature (120ºC)

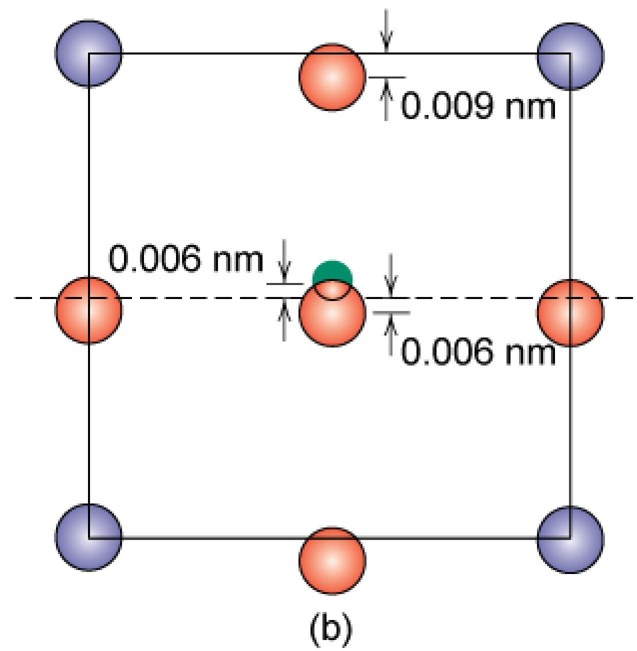


Fig. 18.35, *Callister & Rethwisch 8e.*

12.14 The Hall Effect

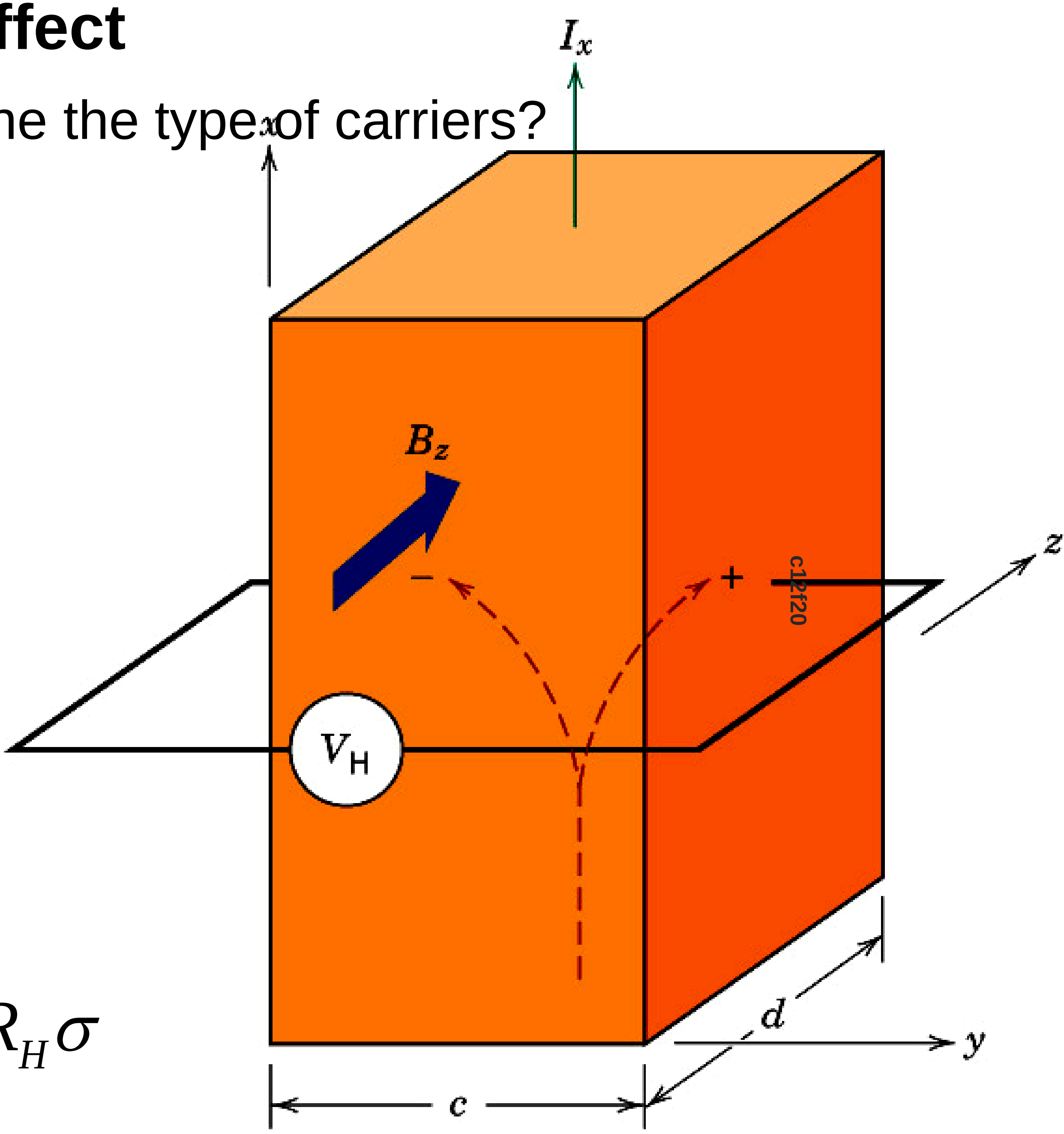
How we can determine the type of carriers?
Use magnetic fields
The Hall voltage

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

The Hall coefficient

$$R_H = \frac{1}{ne}$$

$$\mu_e = \frac{\sigma}{ne} \qquad \mu_e = R_H \sigma$$

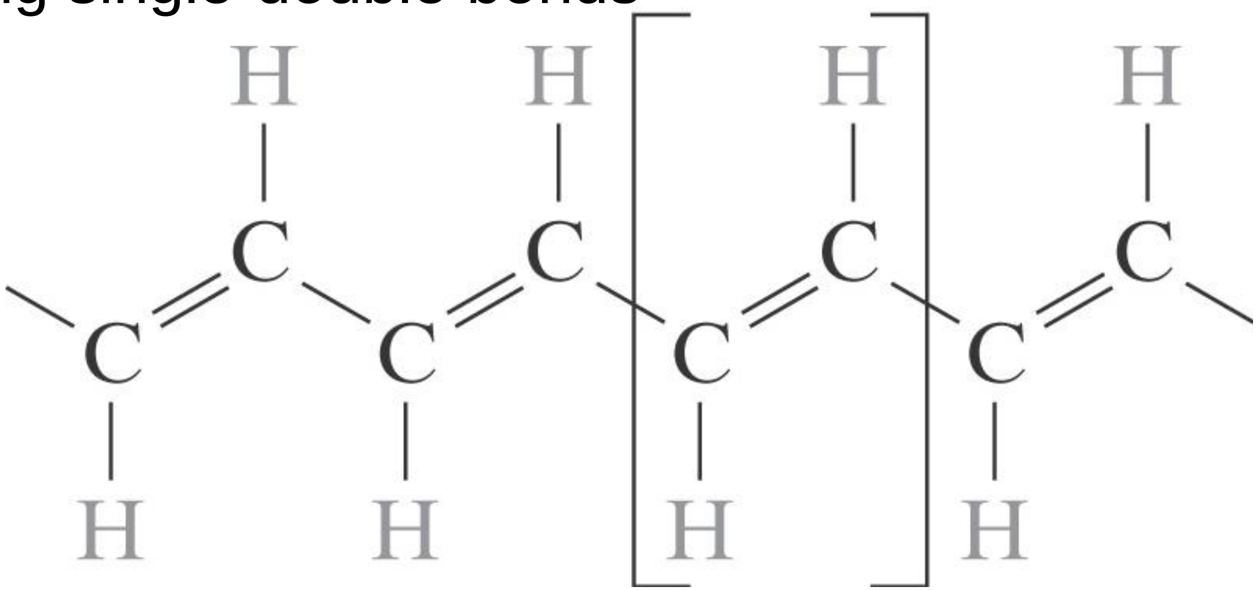


12.17 Electrical properties of polymers

Usually poor conductors of electricity
Mechanism not well-understood
Conduction in polymers of high purity is electronic

Conducting Polymers

Conductivities of 1.5×10^{7} $(\Omega\text{-m})^{-1}$
Even polyacetylene
Due to alternating single-double bonds



Summary

- Electrical *conductivity* and *resistivity* are:
  - -- material parameters
  - -- geometry independent
- Conductors, semiconductors, and insulators...
  - -- differ in range of conductivity values
  - -- differ in availability of electron excitation states
- For metals, *resistivity* is increased by
  - -- increasing temperature
  - -- addition of imperfections
  - -- plastic deformation
- For pure semiconductors, *conductivity* is increased by
  - -- increasing temperature
  - -- doping [e.g., adding B to Si (*p*-type) or P to Si (*n*-type)]
- Other electrical characteristics
  - -- ferroelectricity
  - -- piezoelectricity