MATERIALS SCIENCE

SSP 2412

ELECTRICAL PROPERTIES

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Issues to Address

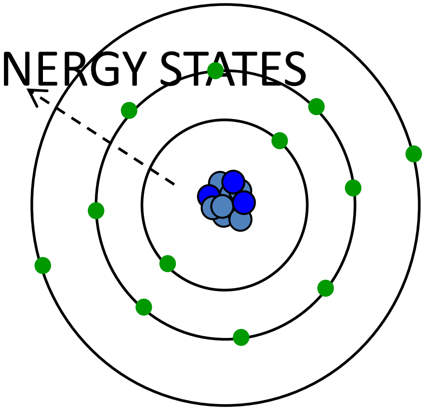
- Electronic structures
- Energy band gaps (Fermi energy level)
- Resistivity & Conductivity:

    Metal

    Semiconductor

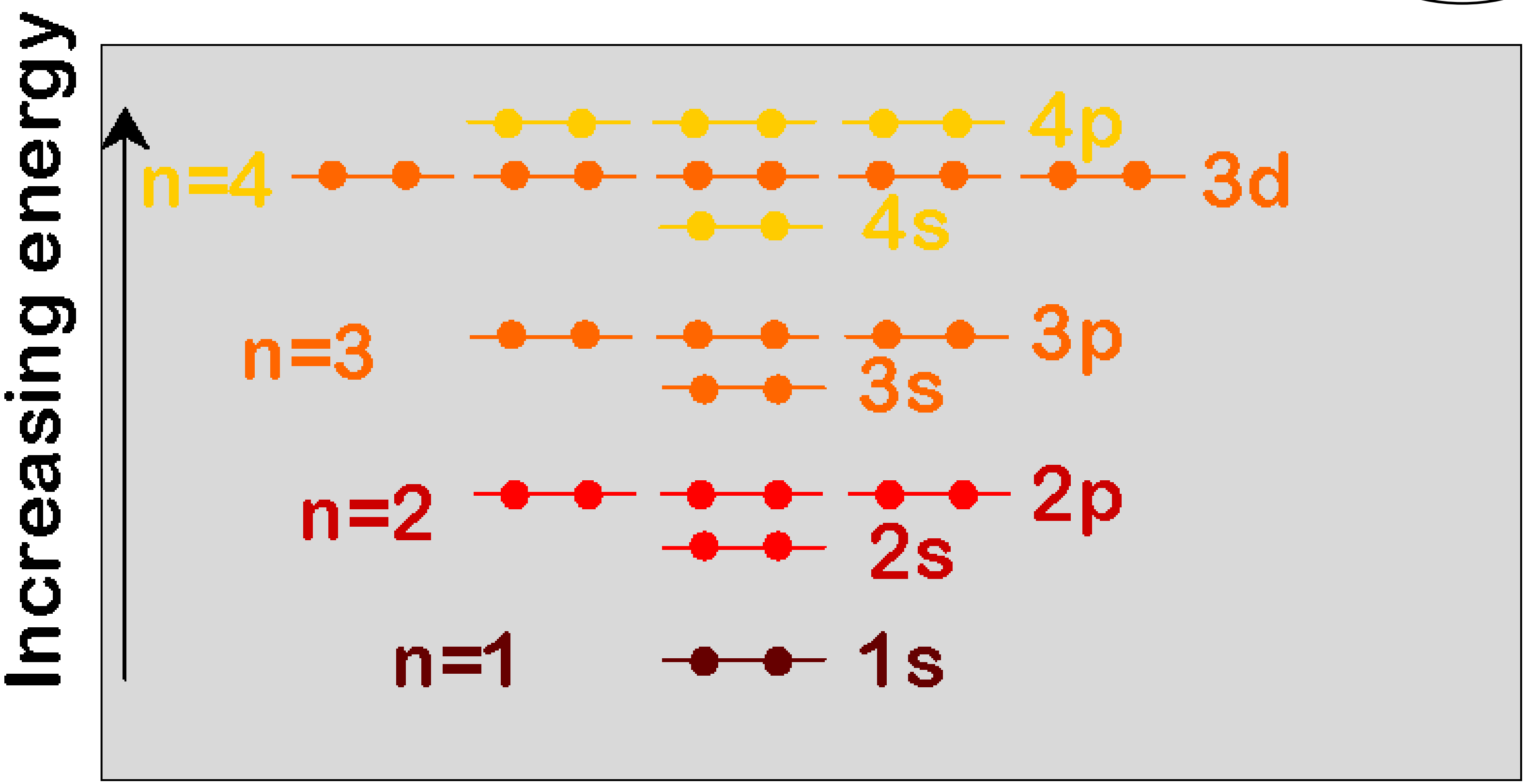
    Insulator (dielectric)

ELECTRONIC STRUCTURES - ELECTRON ENERGY STATES



Electrons...

- **have discrete energy states (levels)**
- **tend to occupy lowest available energy state**



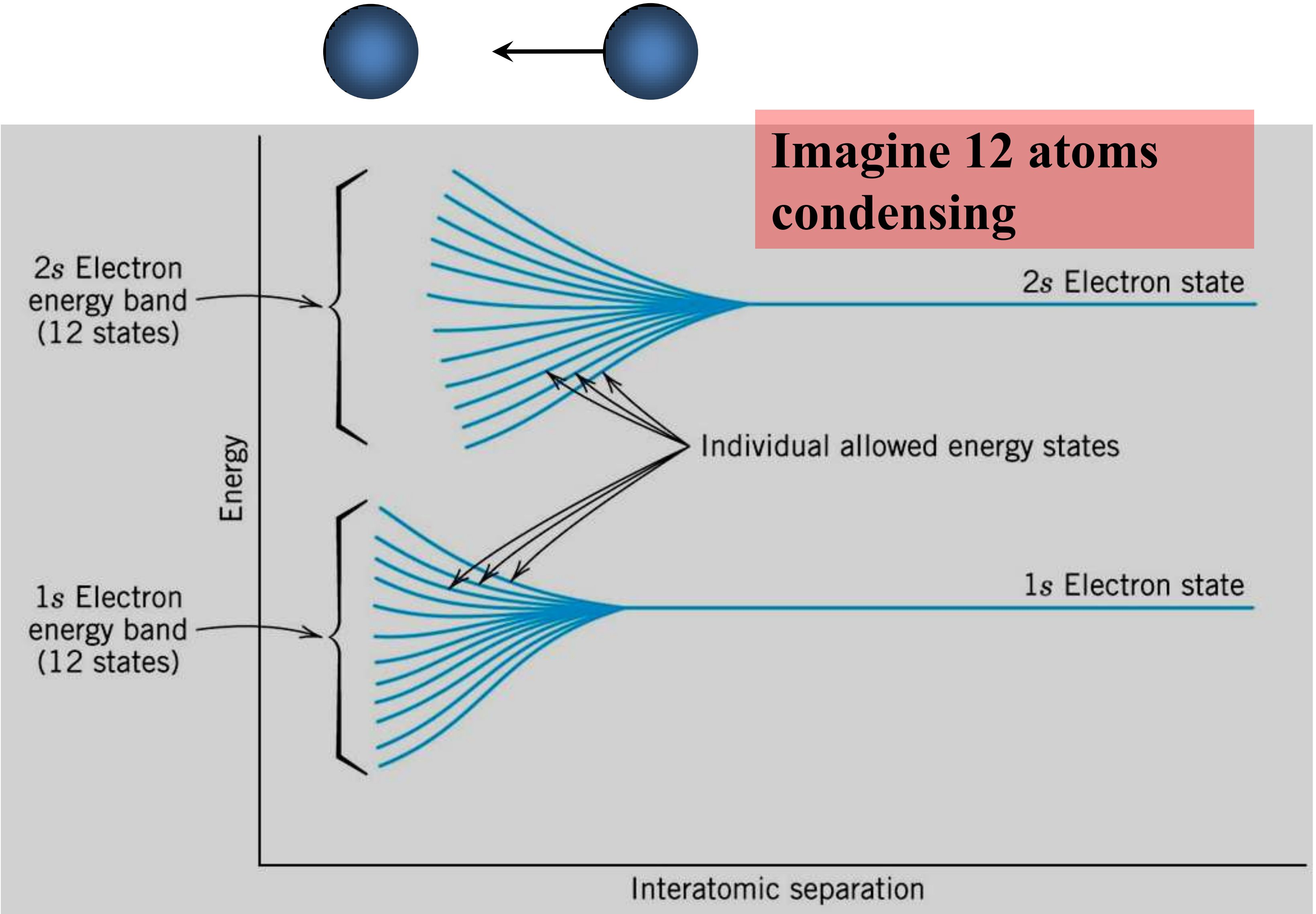
Electronc Structures- Energy Bands

- When atoms come together to form a solid, their valence electrons interact due to Coulomb forces; they feel the electric field produced by their nucleus and that of the other atoms.
- From **Heisenberg's uncertainty principle**, the electrons constrained to a small volume, experience an increase in their energy state. This would imply that the electrons are promoted into the forbidden band gap.
- From the **Pauli exclusion principle**, the number of electrons that can have the same properties is limited (energy level included). In **semiconductors and insulators**, the valence band is filled, and no more electrons can be added.

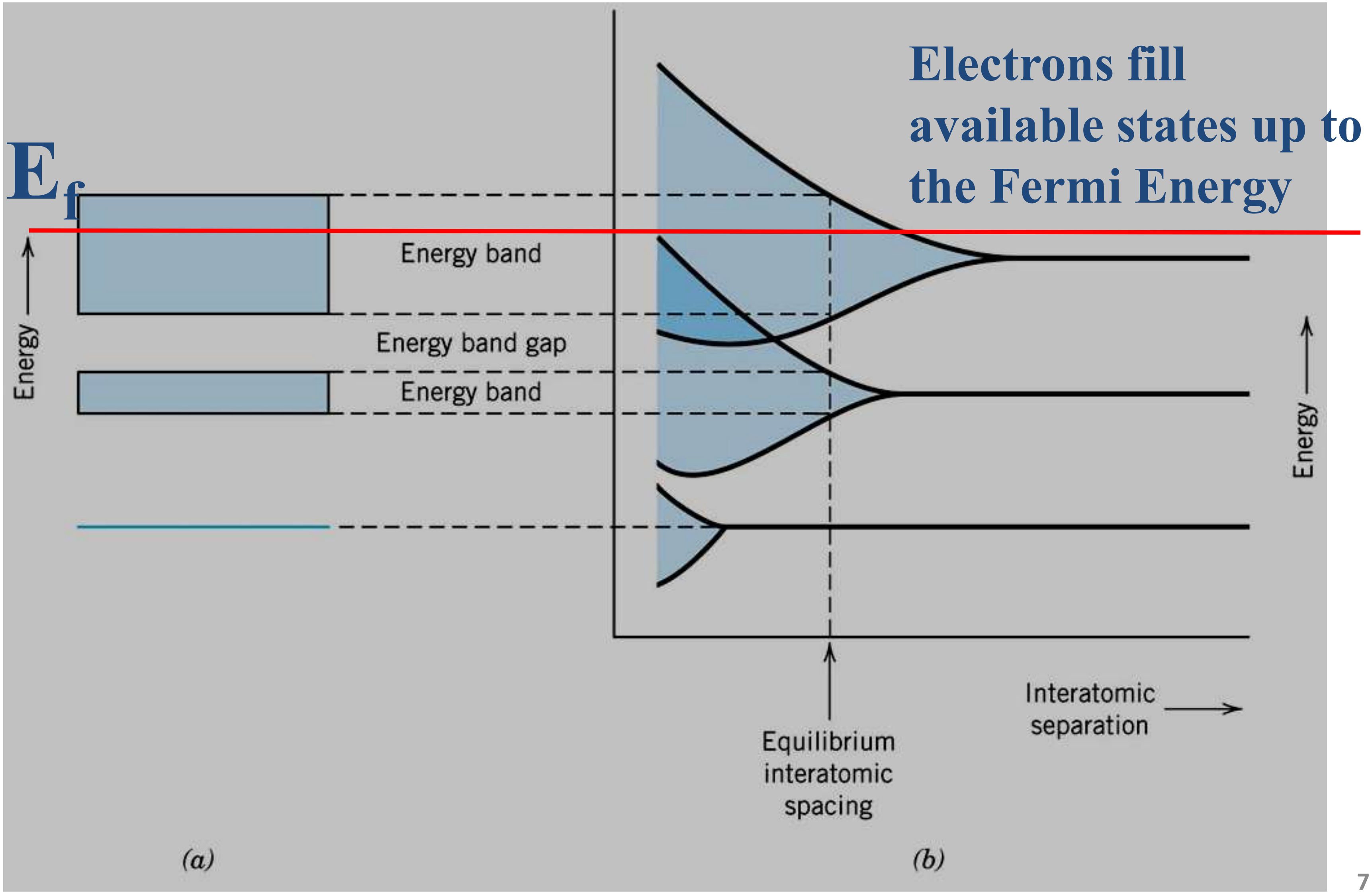
Bands

- As a result, the valence electrons form wide bands when in a solid state.
- The bands are separated by gaps, where electrons cannot exist.
- The precise location of the bands and band gaps depends on the atom, the distance between atoms in the solid, and the atomic arrangement.

When atoms interact, levels split

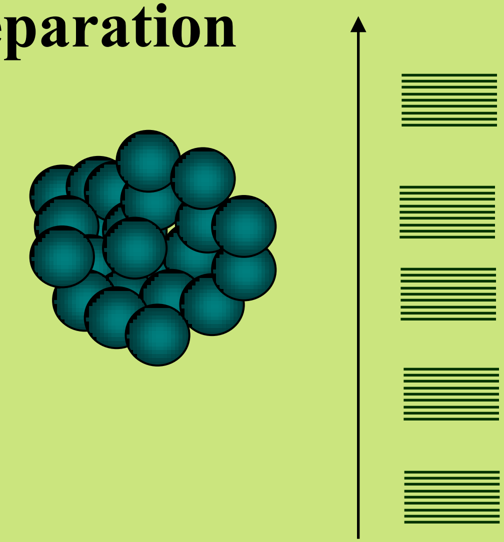


ELECTRONIC BANDS

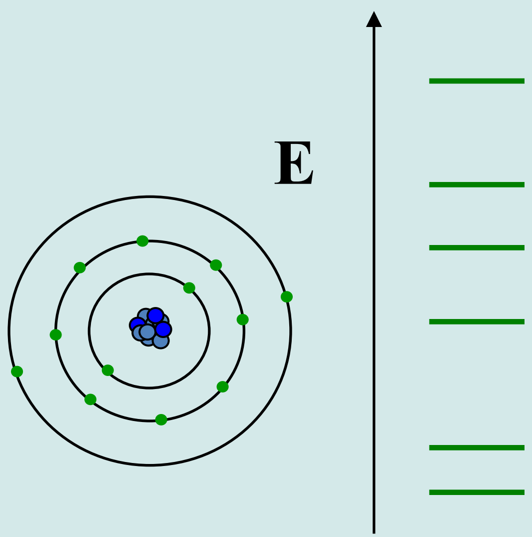


Energy Levels: Discrete to Continuous

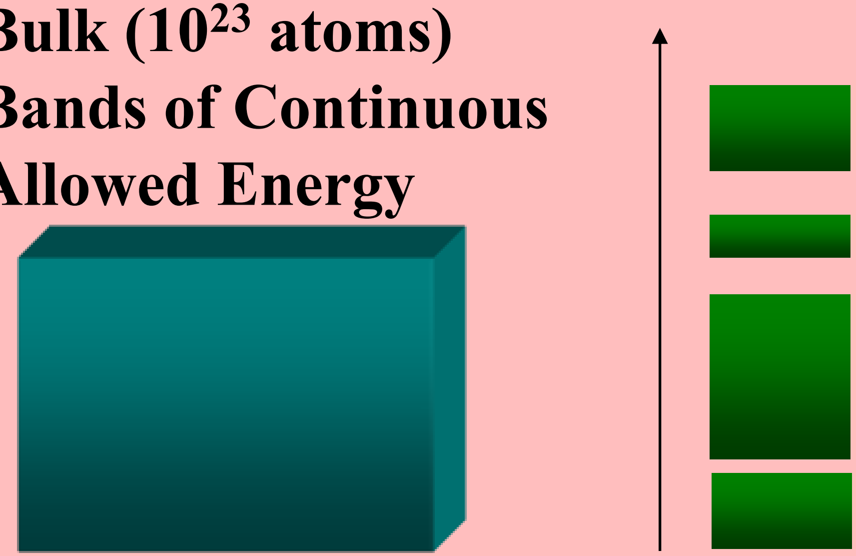
Group of atoms: Energy levels split small separation



Atom: Discrete Energy levels. Large separation

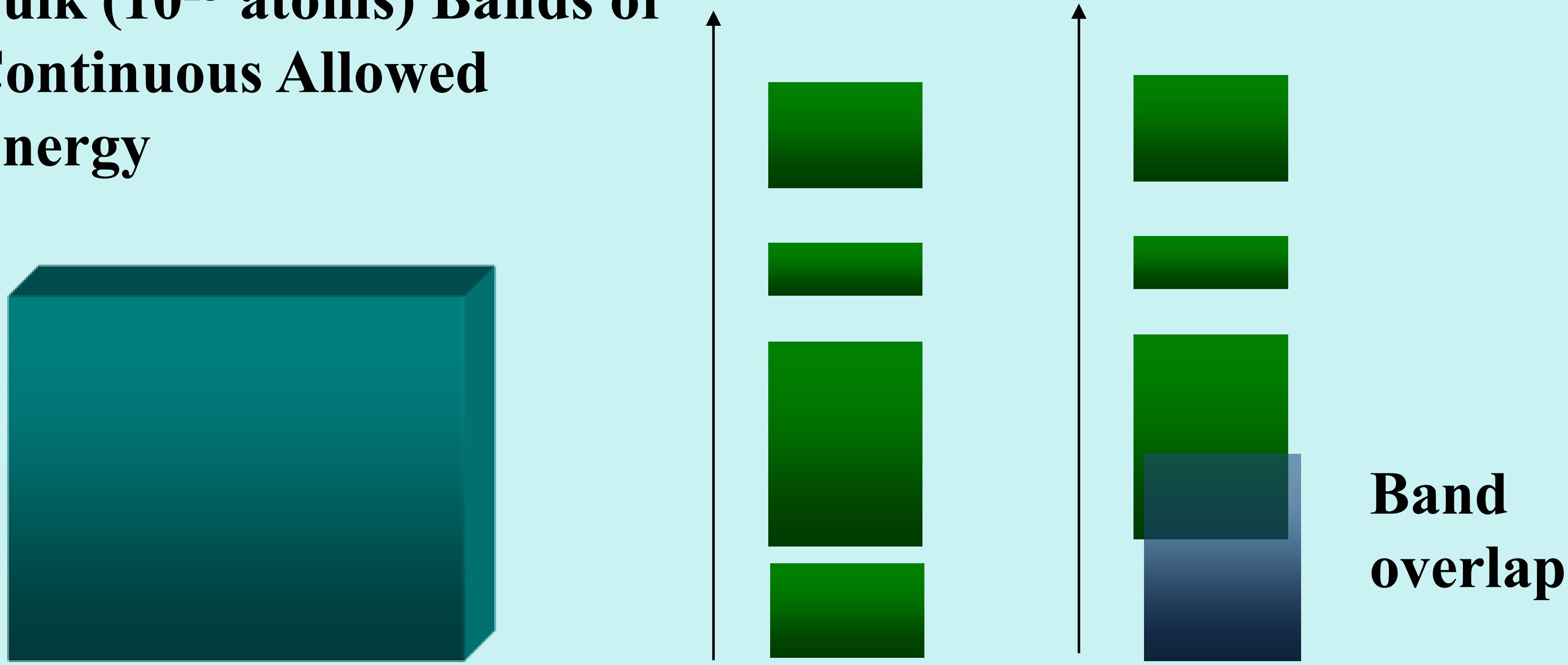


Bulk (10^{23} atoms) Bands of Continuous Allowed Energy

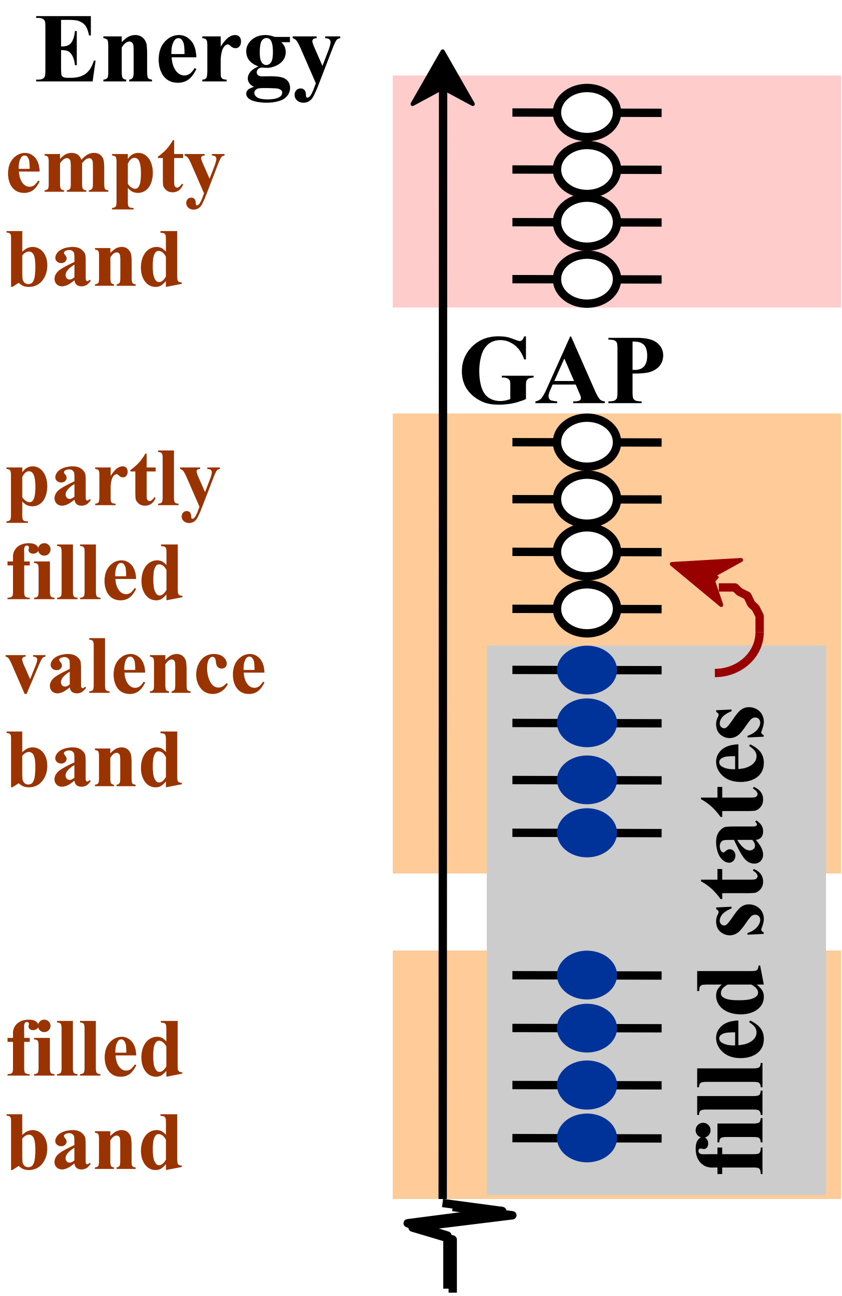


Electronic Band Structure

Bulk (10^{23} atoms) Bands of Continuous Allowed Energy

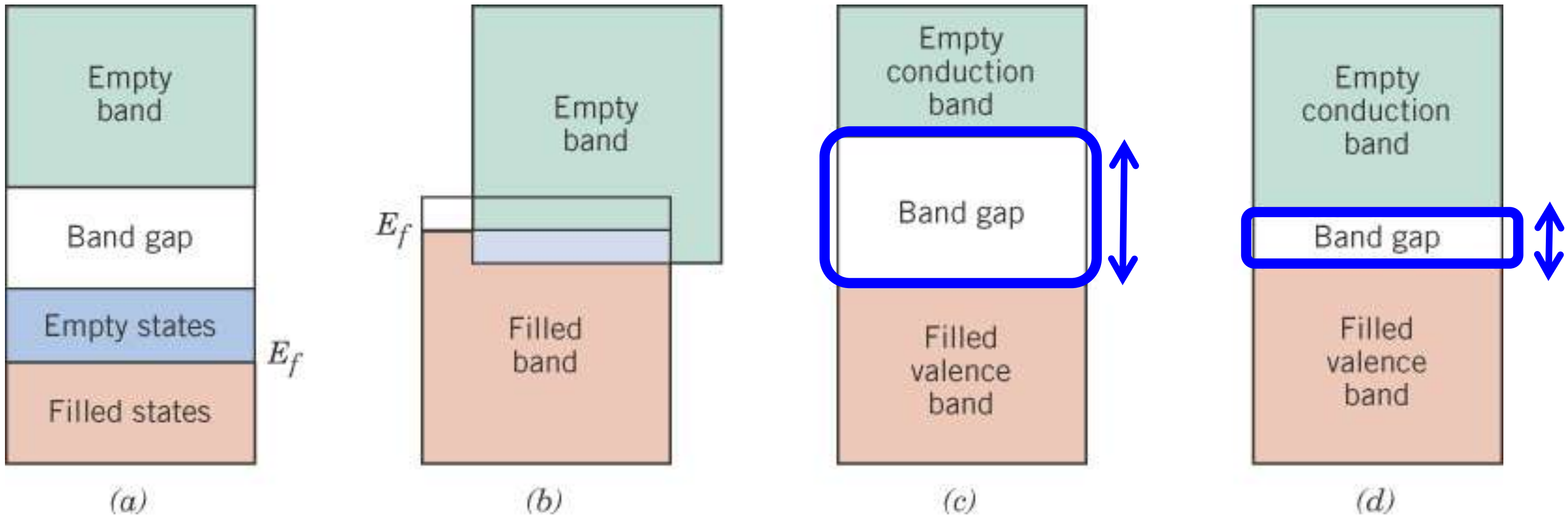


Filling the Bands



Keep in mind that at each energy level there are many, many electrons, not just one.

Electron Structures in Solids at 0 K.



The energy corresponding to the highest filled state is the **Fermi energy, E_f.**

(a) Metal (copper – half filled energy band)

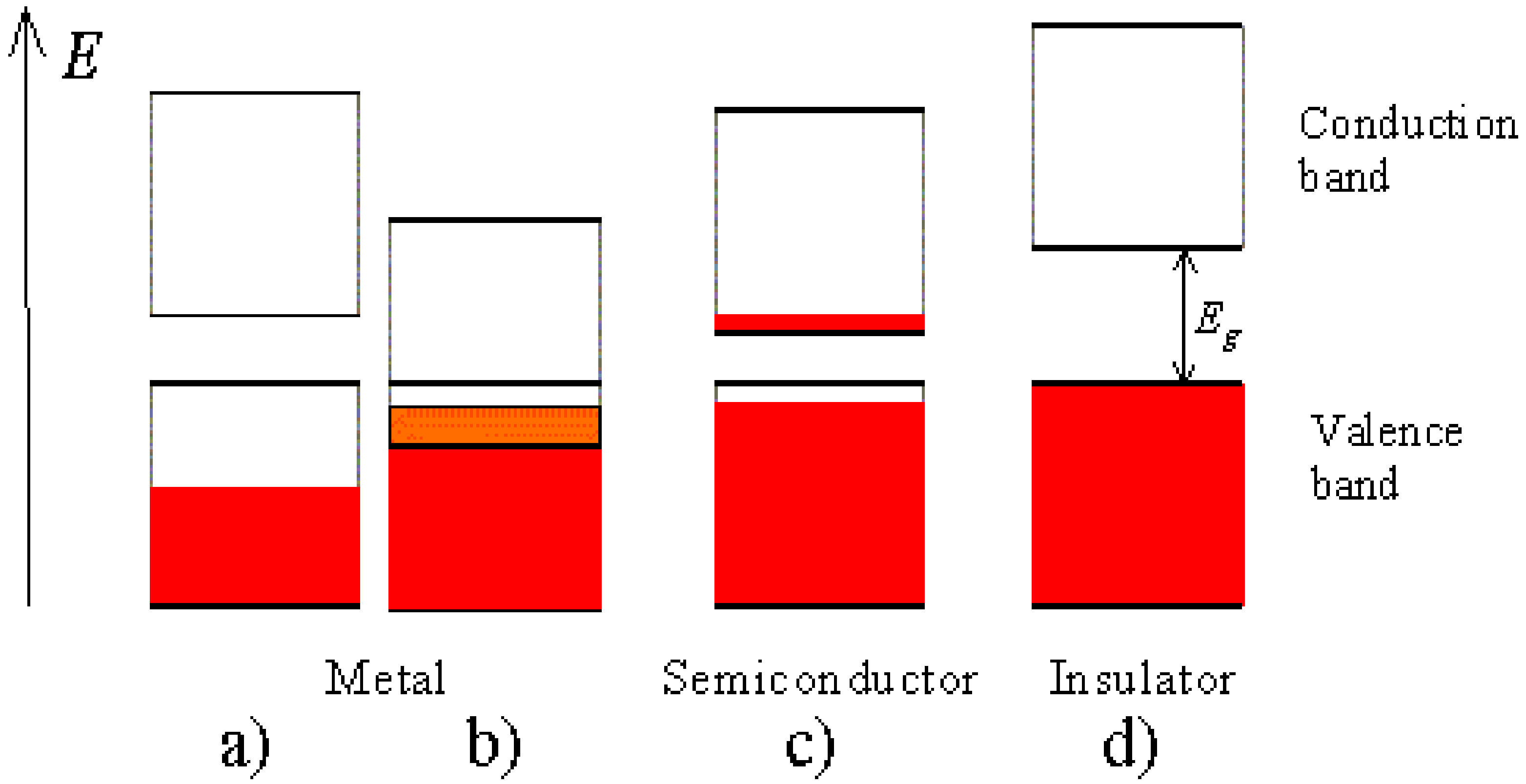
(b) Metal (magnesium – 3s and 3p bands overlap)

(c) Insulator (filled valence band separated by a wide band gap from an empty conduction band)

(d) Semiconductor (filled valence band separated by a narrow band gap from an empty conduction band)

Conduction band - a partially filled or empty energy band

Valence band – the highest partially or completely filled band



Possible energy band diagrams of a crystal. Shown are: a) a half filled band, b) two overlapping bands, c) an almost full band separated by a small bandgap from an almost empty band and d) a full band and an empty band separated by a large bandgap.

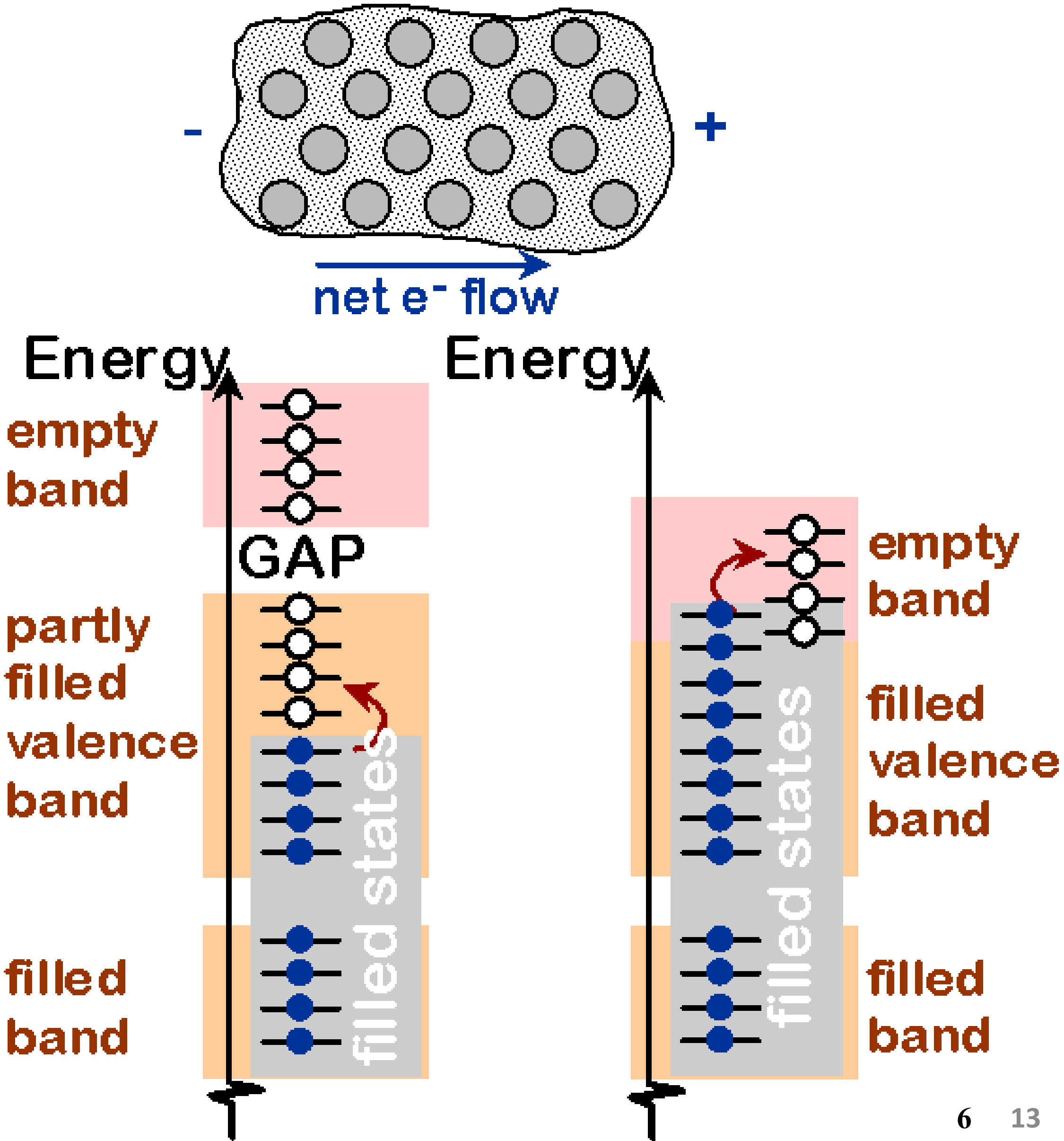
CONDUCTION & ELECTRON TRANSPORT

- **Metals:**

-- Thermal energy puts many electrons into a higher energy state.

- **Energy States:**

-- the cases below for metals show that nearby energy states are accessible by thermal fluctuations.

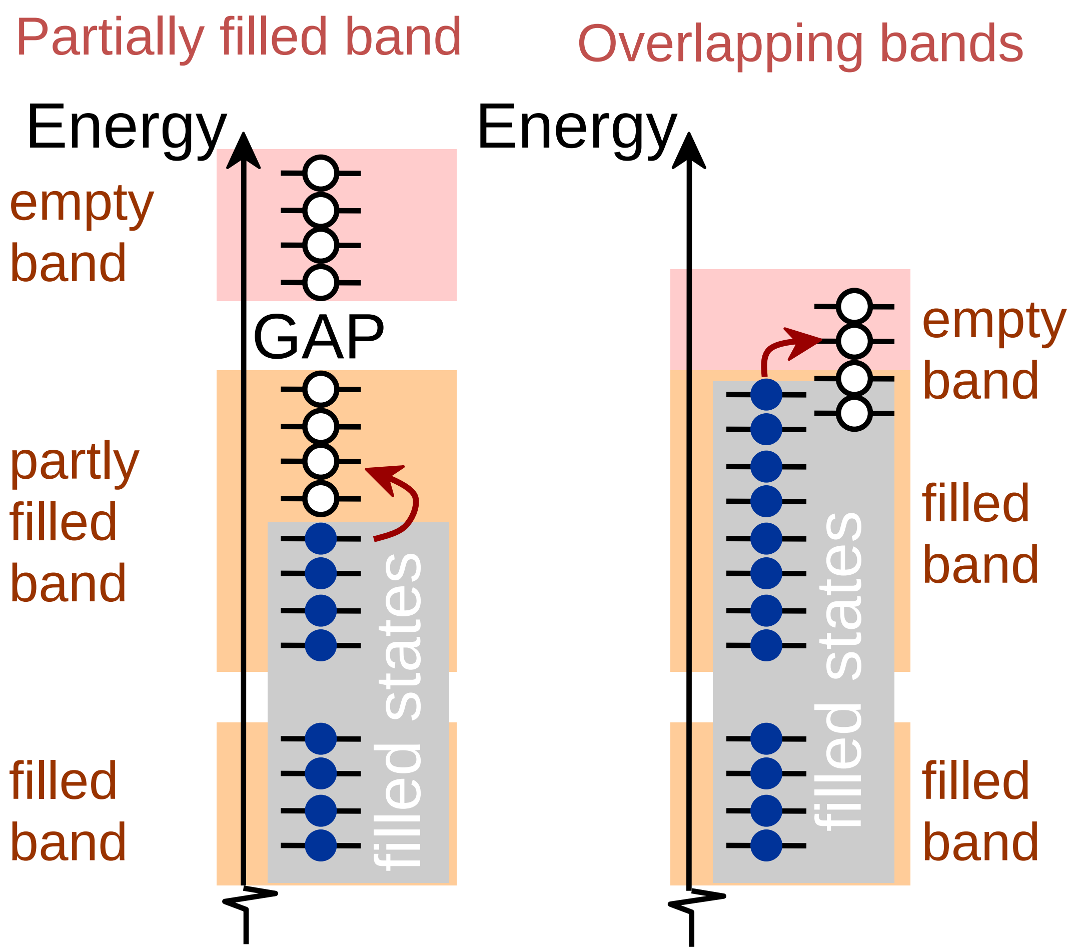


Conduction & Electron Transport

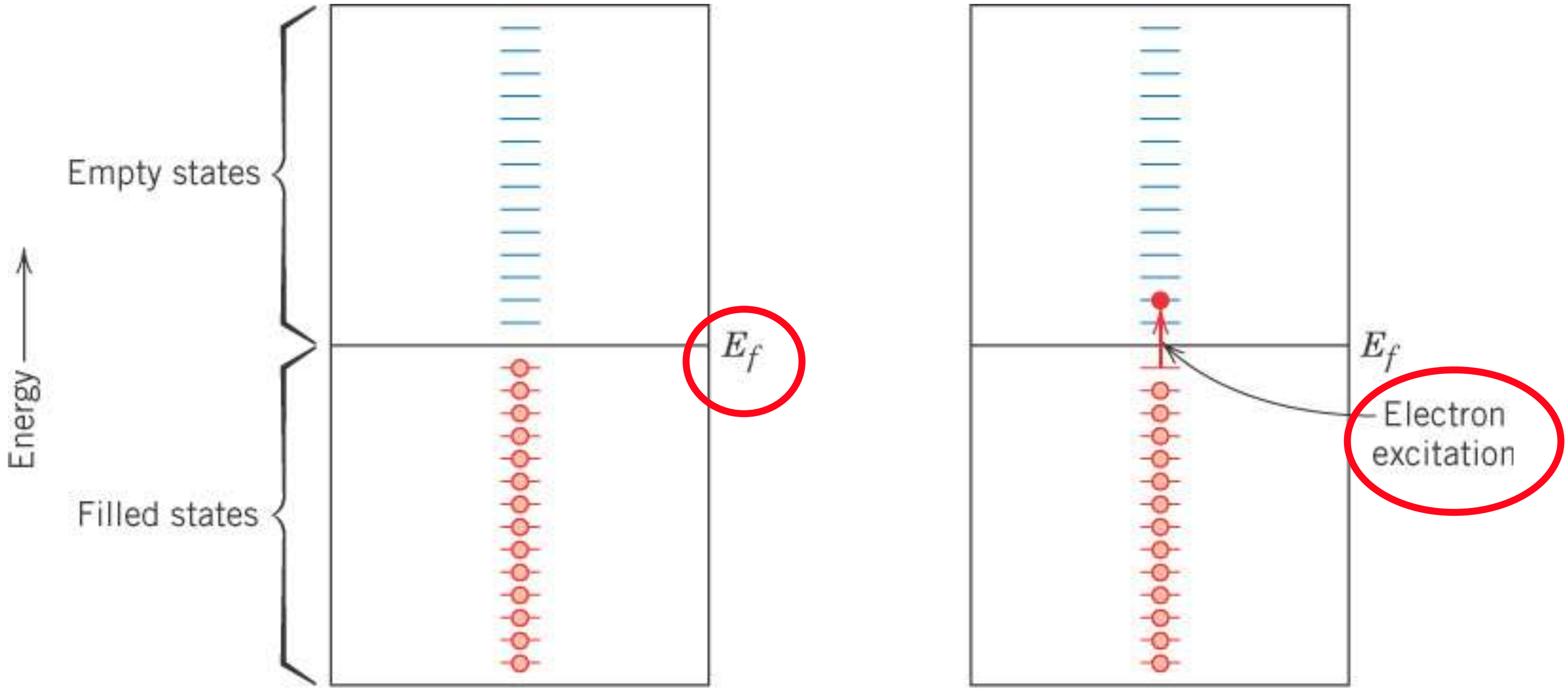
- Metals (Conductors):

-- 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



Metals – Electron States



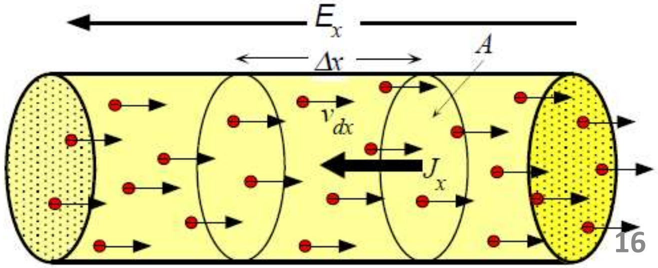
- For metals, little energy is required to promote electrons into the low-lying empty states.
- Energy provided by an electric field is sufficient to excite large numbers of electrons into the conduction band.

Resistivity & Conductivity

- The difference comes down to how the electrons are arranged around the nucleus.
- The laws of quantum physics say that there are only specific bands (or tracks) where an electron can travel.
- First of all, only a very specific number of electrons can travel in each band. Second, which track an electron is in corresponds to how much energy that electron has. And third, some of the bands are closer to each other than others.
- The electrical conductivity (the ability of a substance to conduct an electric current) is the inverse of the resistivity:

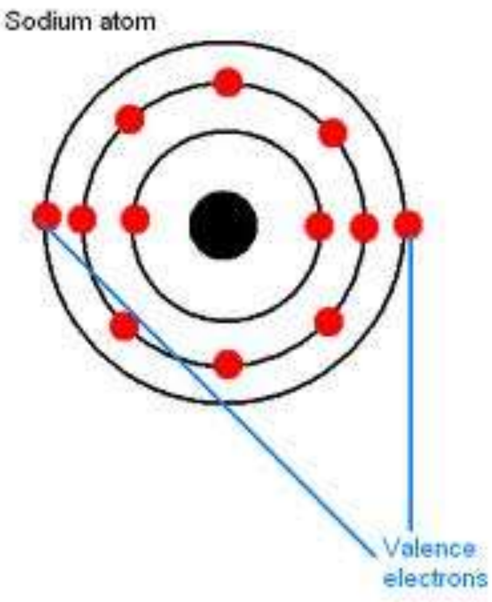
conductivity, **$\sigma = 1/\rho$**

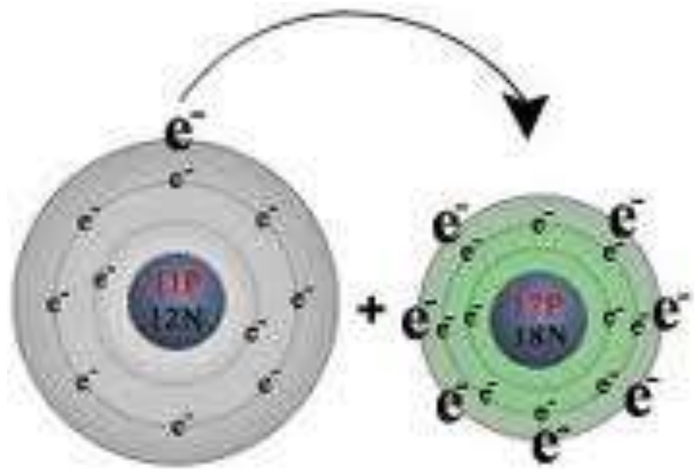
Fig. 2.1: Drift of electrons in a conductor in the presence of an applied electric field. Electrons drift with an average velocity v_{dx} in the x-direction.(E_x is the electric field.)



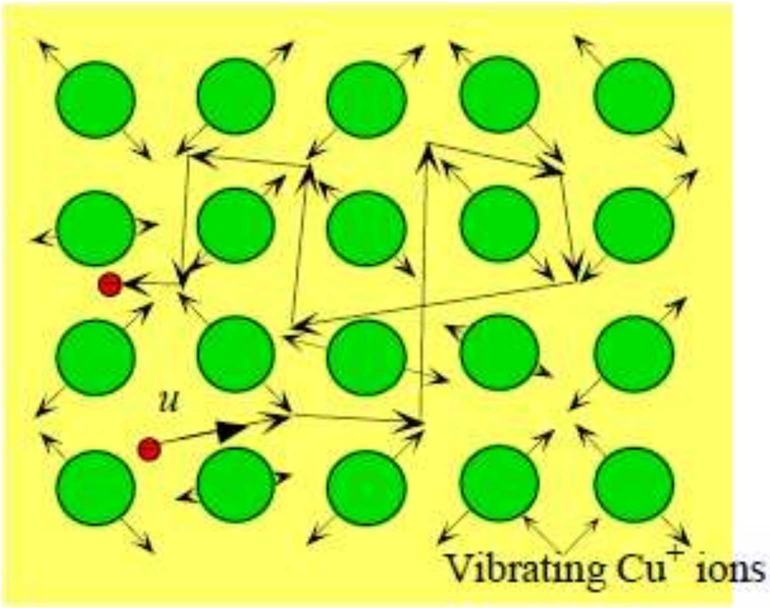
Valence Electrons

Movement of valence electrons



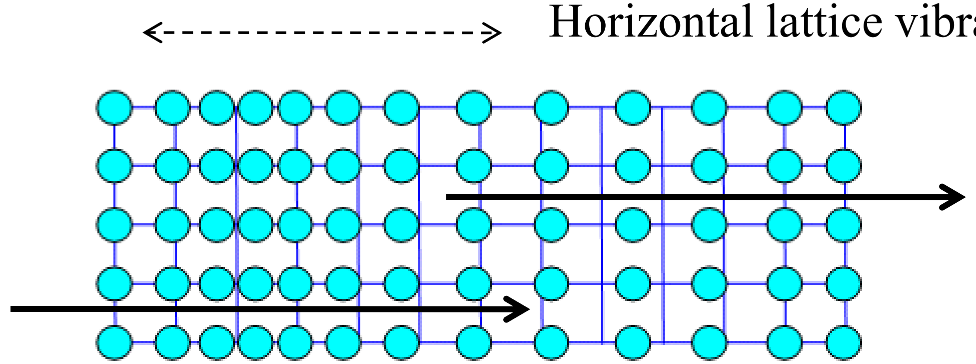


Electron movement



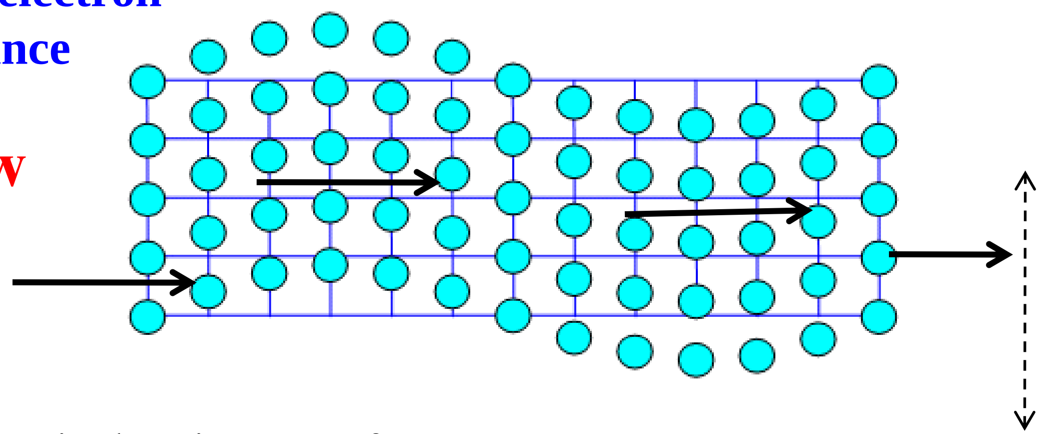
An electron moves about randomly in a metal (with a mean speed u) being frequently and randomly scattered by thermal vibrations of the atoms. In the absence of an applied field there is no net drift in any direction.

Resistance of Movement



Low resistance – high conductivity

Lattice defects also can resist electron flow, thus contributing resistance



High resistance – low conductivity

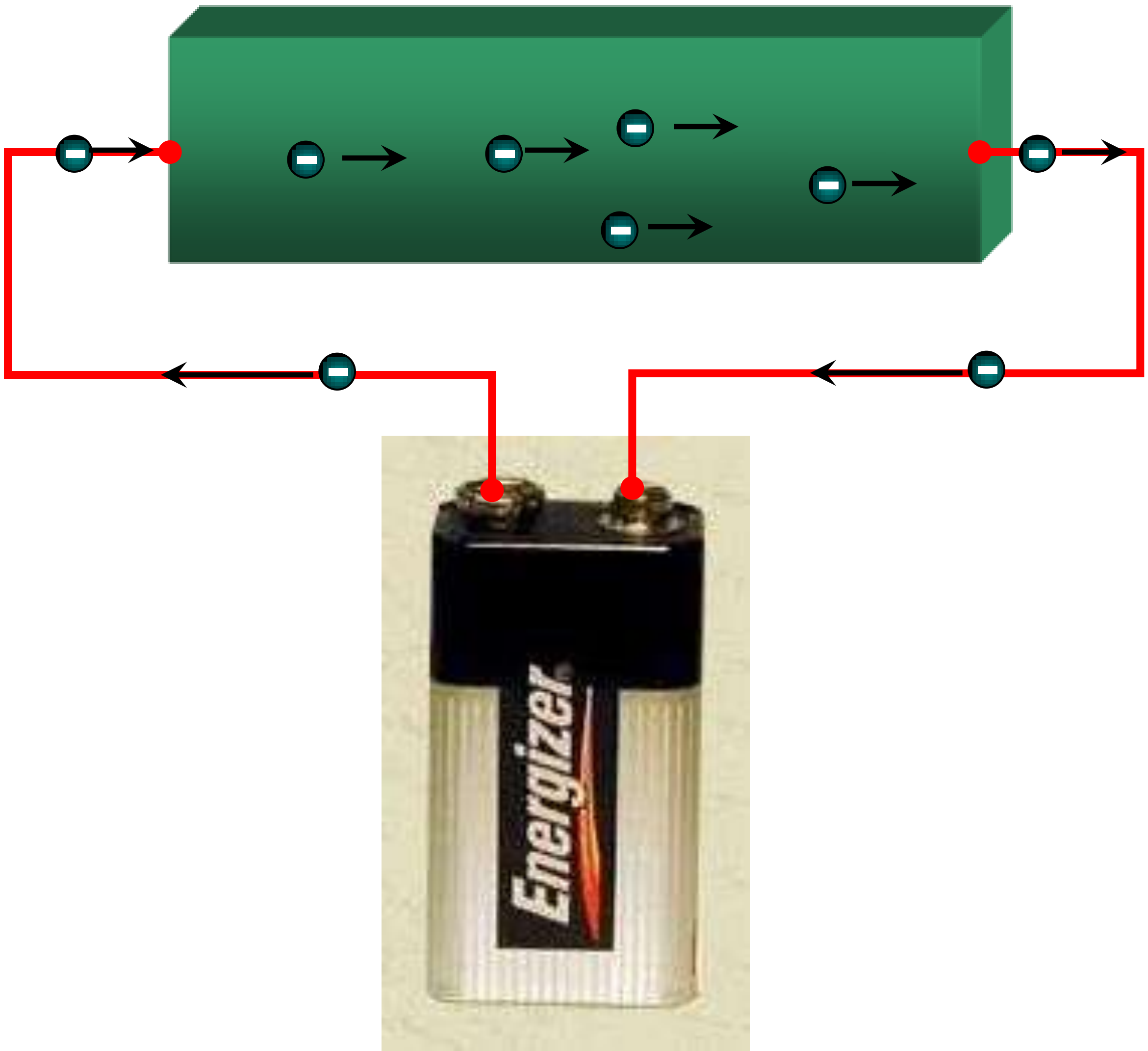
Superconductivity is an electrical resistance of exactly zero which occurs in certain materials (metal & ceramic) below a characteristic temperature.

What is Resistance (Resistivity) ?

Resistance, R : obstruction of current flow. It depends on the intrinsic resistivity ρ of the material [W-m] and on the geometry (length L and area A through which the current passes): **$R = \rho L/A$**

Resistivity, ρ: defines how difficult is it for current to flow. It is a material property that is independent of sample size and geometry.

Electronics



ELECTRICAL CONDUCTION

- **Ohm's Law:**

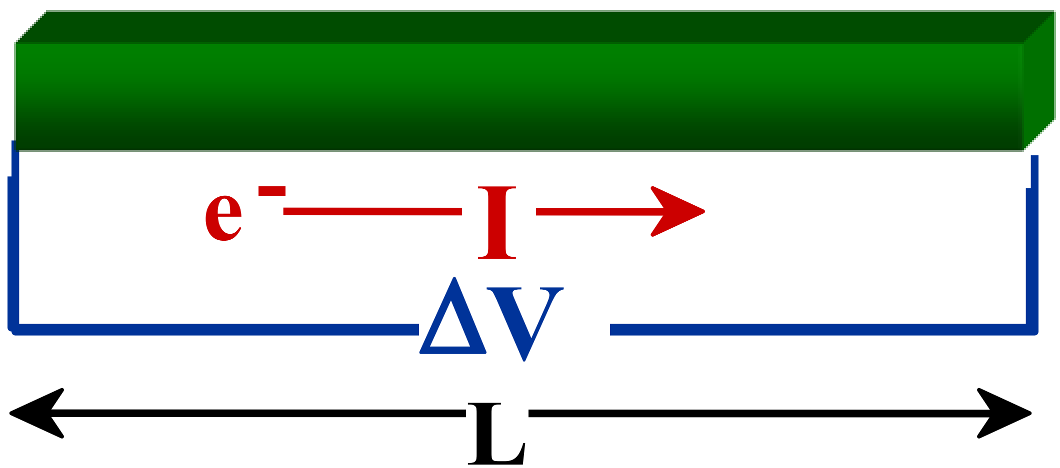
$$\Delta V = I\,R$$

voltage drop (volts)

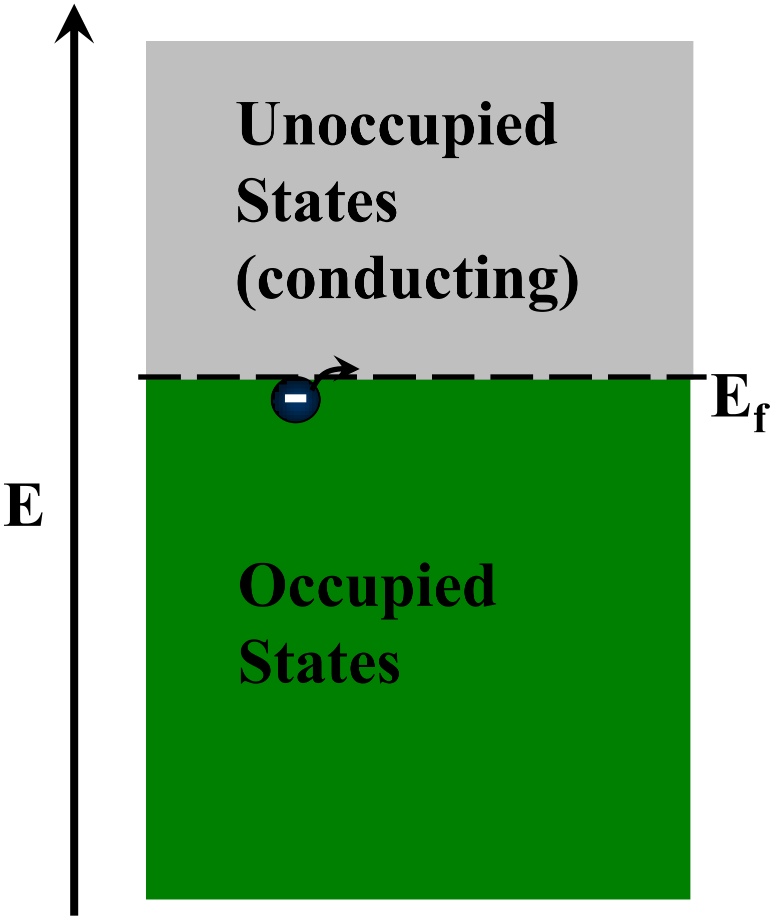
current (amps)

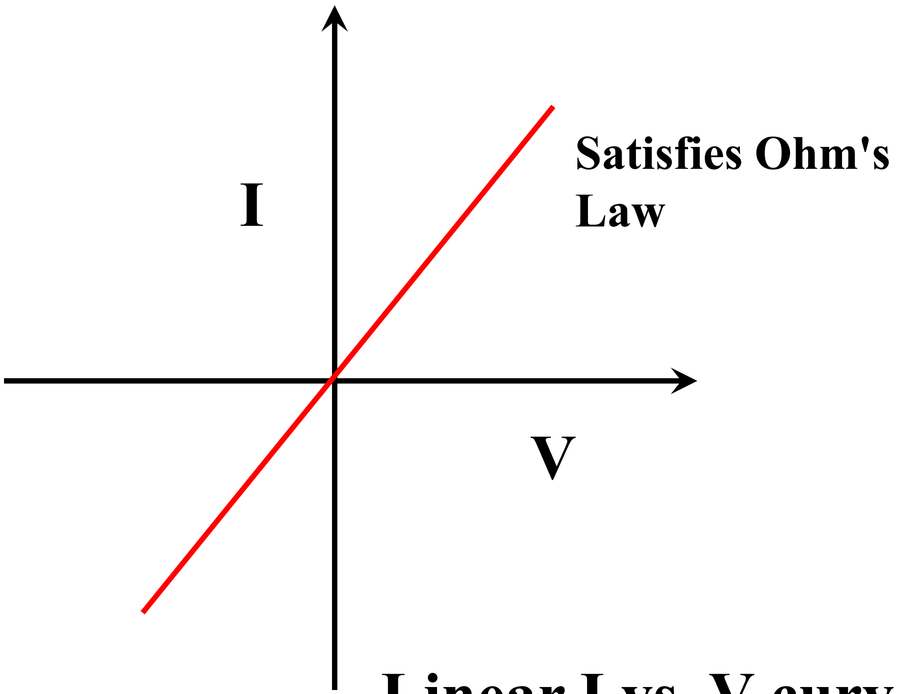
resistance (Ohms)

Extensive Property



Metallic Conduction



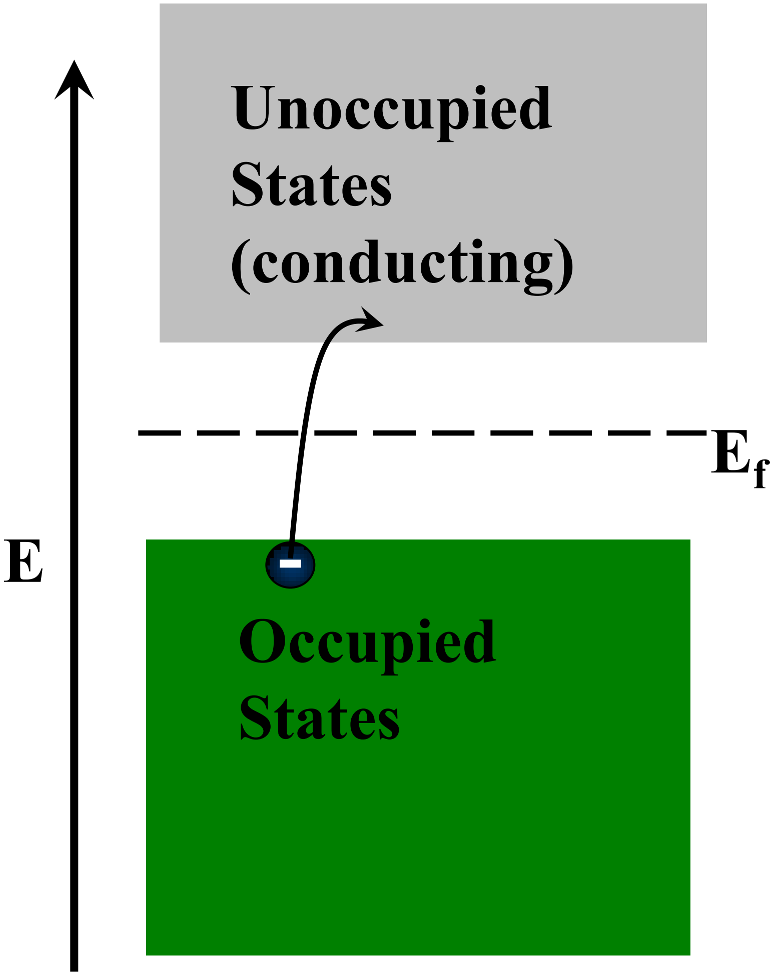


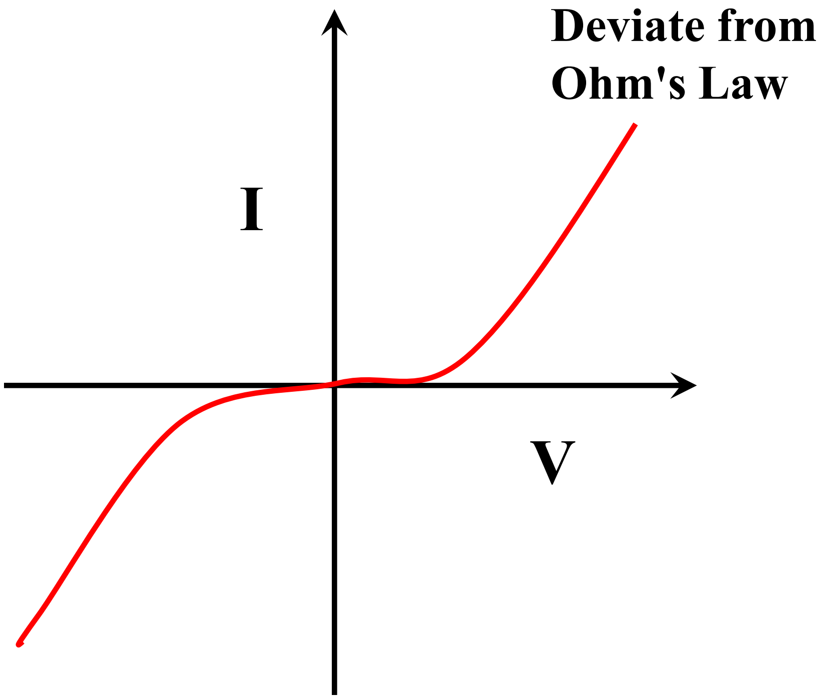
Linear I vs. V curve no matter how small the voltage, we have current.

V=IR

Lower the temp, higher the conductivity

Semiconductor Conduction





Non-Linear I vs. V curve small voltages-no current.

V=IR

Higher the temp, higher the conductivity

Ohm's Law

- When an electrical potential, V [volts, J/C] is applied across a piece of material, a current of magnitude, I [amperes, C/s] flows.
- In most metals, at low voltages, the current is proportional to V, and can be described by
- **Ohm's law**: **I = V/R,** where R is the electrical resistance [ohms, Ω].

- Ohm's Law:

$$V = \boldsymbol{I} R$$

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

current (amps = C/s) → I

resistance (Ohms) → R

Resistivity, ρ and Conductivity, σ:

-- geometry-independent forms of Ohm's Law

$$\frac{\Delta V}{L} = \frac{I}{A}\rho$$

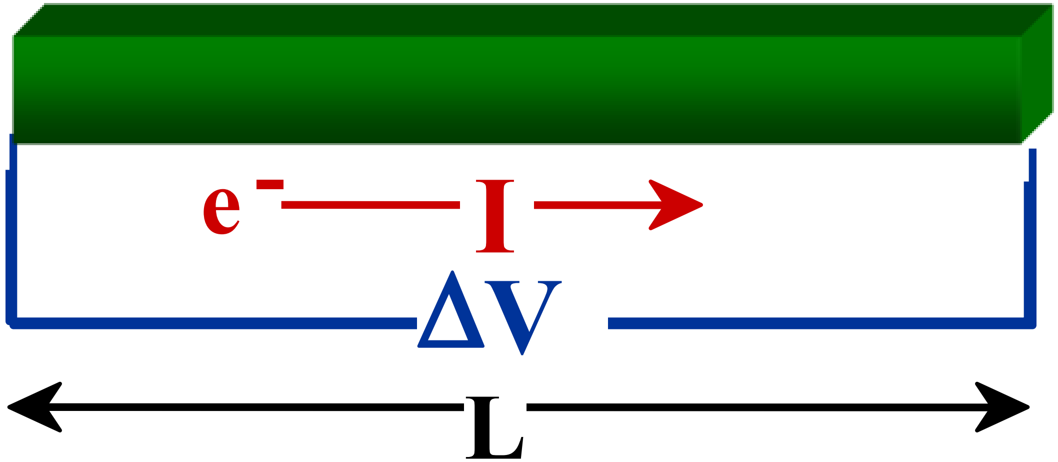
← resistivity (Ohm-m)

Intrinsic Property

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

- **Resistance:**

$$R = \frac{\rho L}{A} = \frac{L}{A\sigma}$$



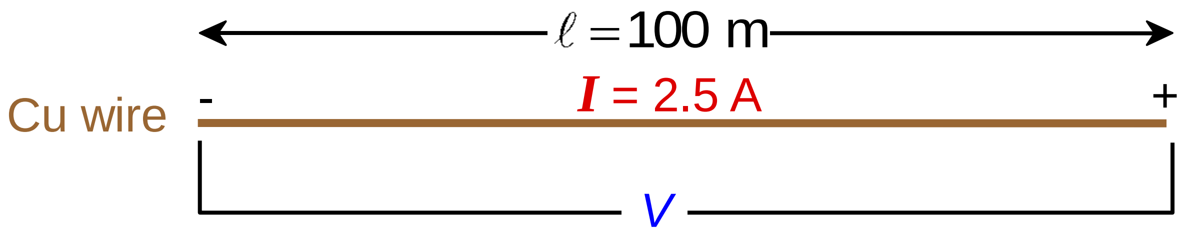
Conductivity

- Electrical conductivity varies between different materials by over 27 orders of magnitude, the greatest variation of any physical property.

- **Metals:** $\sigma > 10^5 \ (\Omega.m)^{-1}$
- **Semiconductors:** $10^{-6} < \sigma < 10^5 \ (\Omega.m)^{-1}$
- **Insulators:** $\sigma < 10^{-6} \ (\Omega.m)^{-1}$

Example: Conductivity Problem

What is the minimum diameter (*D*) of the wire so that $V < 1.5$ V?



$$R = \frac{\rho \ell}{A} = \frac{V}{I}$$

$$R = \frac{\ell}{\sigma A} = \frac{V}{I}$$

$$A = \frac{\pi D^2}{4} = \frac{\ell I}{\sigma V}$$

$$R = \frac{\ell}{A\sigma} = \frac{V}{I}$$

- ℓ: 100 m
- V: < 1.5 V
- I: 2.5 A
- $A = \frac{\pi D^2}{4}$
- σ: 6.07 x 10^7 (Ohm-m)$^{-1}$

$$D^2 = 4\frac{\ell I}{\sigma V \pi} = \frac{4(100m)(2.5A)}{(6.07x10^7/\Omega m)(1.49V)(\pi)}$$

Solve to get $D > 1.876$ mm

Room-Temperature Electrical Conductivities for Nine Common Metals and Alloys

Metal	*Electrical Conductivity* $[(\Omega\text{-}m)^{-1}]$
Silver	6.8×10^7
Copper	6.0×10^7
Gold	4.3×10^7
Aluminum	3.8×10^7
Brass (70 Cu–30 Zn)	1.6×10^7
Iron	1.0×10^7
Platinum	0.94×10^7
Plain carbon steel	0.6×10^7
Stainless steel	0.2×10^7

In a metal, n is large. In an insulator, n is very, very small.

$$\sigma = n\,|e|\,\mu_e$$

σ = conductivity; n = number of electrons, |e| = charge = 1.6×10^{-19} C, μ = electron mobility

CONDUCTIVITY: COMPARISON

- Room T values $(\text{Ohm-m})^{-1}$

METALS conductors

Silver	6.8×10^{7}
Copper	6.0×10^{7}
Iron	1.0×10^{7}

CERAMICS

Soda-lime glass	10^{-10}
Concrete	10^{-9}
Aluminum oxide	$<10^{-13}$

SEMICONDUCTORS

Silicon	4×10^{-4}
Germanium	2×10^{0}
GaAs	10^{-6}

semiconductors

POLYMERS

Polystyrene	$<10^{-14}$
Polyethylene	10^{-15}-10^{-17}

insulators

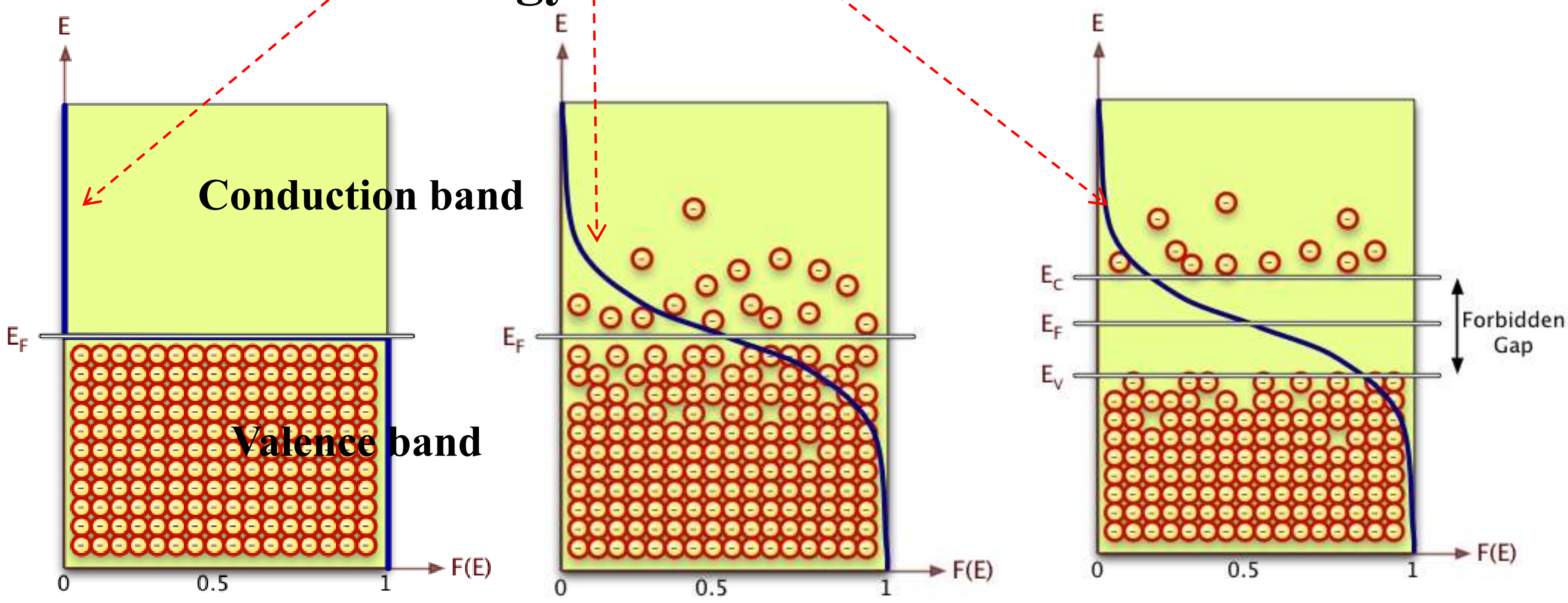
Band gap Energy

- When light shines on crystalline silicon, electrons within the crystal lattice may be freed. But only photons (packets of light energy) with a specific level of energy can free electrons in the semiconductor material from their atomic bonds to produce an electric current.
- This level of energy (band gap energy) is the amount of energy required to dislodge an electron from its covalent bond and allow it to become part of an electrical circuit.
- To free an electron, the energy of a photon must be at least as great as the band gap energy.
- Photons with more energy than the band gap energy will expend that extra amount as heat when freeing electrons.

Fermi Level - http://cnx.org/content/m13458/latest/

Fermi Level is defined as the highest occupied molecular orbital in the valence band at 0 K.

The Fermi function, *f(E)* gives the probability that a state, S at energy, E is occupied by an electron, given that E is an allowed energy level.



Metal, T=O K **Metal, T>O K** **Semiconductor T>O K**

Periodic System of Elements

Dimitri Mendeleev (1869)

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIII
1 H Hydrogen 1.01 $1s^1$																	2 He Helium 4.00 $1s^2$
3 Li Lithium 6.94 $2s^1$	4 Be Beryllium 9.01 $2s^2$											5 B Boron 10.8 $2p^1$	6 C Carbon 12.0 $2p^2$	7 N Nitrogen 14.0 $2p^3$	8 O Oxygen 16.0 $2p^4$	9 F Fluorine 19.0 $2p^5$	10 Ne Neon 20.2 $2p^6$
11 Na Sodium 23.0 $3s^1$	12 Mg Magnesium 24.3 $3s^2$											13 Al Aluminum 27.0 $3p^1$	14 Si Silicon 28.1 $3p^2$	15 P Phosphorous 31.0 $3p^3$	16 S Sulfur 32.1 $3p^4$	17 Cl Chlorine 35.5 $3p^5$	18 Ar Argon 40.0 $3p^6$
19 K Potassium 39.1 $4s^1$	20 Ca Calcium 40.1 $4s^2$	21 Sc Scandium 45.0 $3d^14s^2$	22 Ti Titanium 47.9 $3d^24s^2$	23 V Vanadium 50.9 $3d^34s^2$	24 Cr Chromium 52.0 $3d^54s^1$	25 Mn Manganese 54.9 $3d^54s^2$	26 Fe Iron 55.9 $3d^64s^2$	27 Co Cobalt 58.9 $3d^74s^2$	28 Ni Nickel 58.7 $3d^84s^2$	29 Cu Copper 63.5 $3d^{10}4s^1$	30 Zn Zinc 65.4 $3d^{10}4s^2$	31 Ga Gallium 69.7 $4p^1$	32 Ge Germanium 72.6 $4p^2$	33 As Arsenic 74.9 $4p^3$	34 Se Selenium 79.0 $4p^4$	35 Br Bromine 79.9 $4p^5$	36 Kr Krypton 83.8 $4p^6$
37 Rb Rubidium 85.5 $5s^1$	38 Sr Strontium 87.6 $5s^2$	39 Y Yttrium 88.9 $4d^15s^2$	40 Zr Zirconium 91.2 $4d^25s^2$	41 Nb Niobium 92.9 $4d^45s^1$	42 Mo Molybdenum 95.9 $4d^55s^1$	43 Tc Technetium 98 $4d^55s^2$	44 Ru Ruthenium 101 $4d^75s^1$	45 Rh Rhodium 103 $4d^85s^1$	46 Pd Palladium 106 $4d^{10}$	47 Ag Silver 108 $4d^{10}5s^1$	48 Cd Cadmium 112 $4d^{10}5s^2$	49 In Indium 115 $5p^1$	50 Sn Tin 119 $5p^2$	51 Sb Antimony 122 $5p^3$	52 Te Tellurium 128 $5p^4$	53 I Iodine 127 $5p^5$	54 Xe Xenon 131 $5p^6$
55 Cs Cesium 133 $6s^1$	56 Ba Barium 137 $6s^2$	57 La* Lanthanum 139 $5d^16s^2$	72 Hf Hafnium 178 $5d^26s^2$	73 Ta Tantalum 181 $5d^36s^2$	74 W Tungsten 184 $5d^46s^2$	75 Re Rhenium 186 $5d^56s^2$	76 Os Osmium 190 $5d^66s^2$	77 Ir Iridium 192 $5d^76s^2$	78 Pt Platinum 195 $5d^96s^1$	79 Au Gold 197 $5d^{10}6s^1$	80 Hg Mercury 201 $5d^{10}6s^2$	81 Tl Thallium 204 $6p^1$	82 Pb Lead 207 $6p^2$	83 Bi Bismuth 209 $6p^3$	84 Po Polonium 209 $6p^4$	85 At Astatine 210 $6p^5$	86 Rn Radon 222 $6p^6$
87 Fr Francium 223 $7s^1$	88 R Radium 226 $7s^2$	89 Ac** Actinium 227 $6d^17s^2$															
Alkaline metals	Alkaline-earth metals									Coinage metals			Elemental semiconductors			Halogens	Noble gases

Explanation

11 ← Atomic number (*i. e.* # of protons)
23.0 ← Atomic weight
Na Sodium
$3s^1$ ← Outer shell electron configuration

Lanthanides*	58 Ce Cerium 140 $4f^15d^16s^2$	59 Pr Praseodymium 141 $4f^36s^2$	60 Nd Neodymium 144 $4f^46s^2$	61 Pm Promethium 145 $4f^56s^2$	62 Sm Samarium 150 $4f^66s^2$	63 Eu Europium 152 $4f^76s^2$	64 Gd Gadolinium 157 $4f^75d^16s^2$	65 Tb Terbium 159 $4f^96s^2$	66 Dy Dysprosium 163 $4f^{10}6s^2$	67 Ho Holmium 157 $4f^{11}6s^2$	68 Er Erbium 167 $4f^{12}6s^2$	69 Tm Thulium 169 $4f^{13}6s^2$	70 Yb Ytterbium 173 $4f^{14}6s^2$	71 Lu Lutetium 175 $5d^16s^2$
Actinides**	90 Th Thorium 232 $6d^27s^2$	91 Pa Protactinium 231 $5f^26d^17s^2$	92 U Uranium 238 $5f^36d^17s^2$	93 Np Neptunium 237 $5f^46d^17s^2$	94 Pu Plutonium 244 $5f^67s^2$	95 Am Americium 243 $5f^77s^2$	96 Cm Curium 247 $5f^76d^17s^2$	97 Bk Berkelium 247 $5f^97s^2$	98 Cf Californium 251 $5f^{10}7s^2$	99 Es Einsteinium 252 $5f^{11}7s^2$	100 Fm Fermium 257 $5f^{11}7s^2$	101 Md Mendelevium 258 $5f^{11}7s^2$	102 No Nobelium 259 $5f^{11}7s^2$	103 Lr Lawrencium 260 $6d^17s^2$

Rare-earth elements

ELECTRICAL CONDUCTIION IN NON-METALLIC MATERIALS

- Insulators
- Semiconductors

Insulators

- In insulators there are no free electrons to move throughout the material.
- Interatomic bonding is ionic or strongly covalent. The valence electrons are tightly bonded, highly localized and not free to scatter throughout the crystal.
- The band-gap is large, the valence band is full, and the conduction band is empty.

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

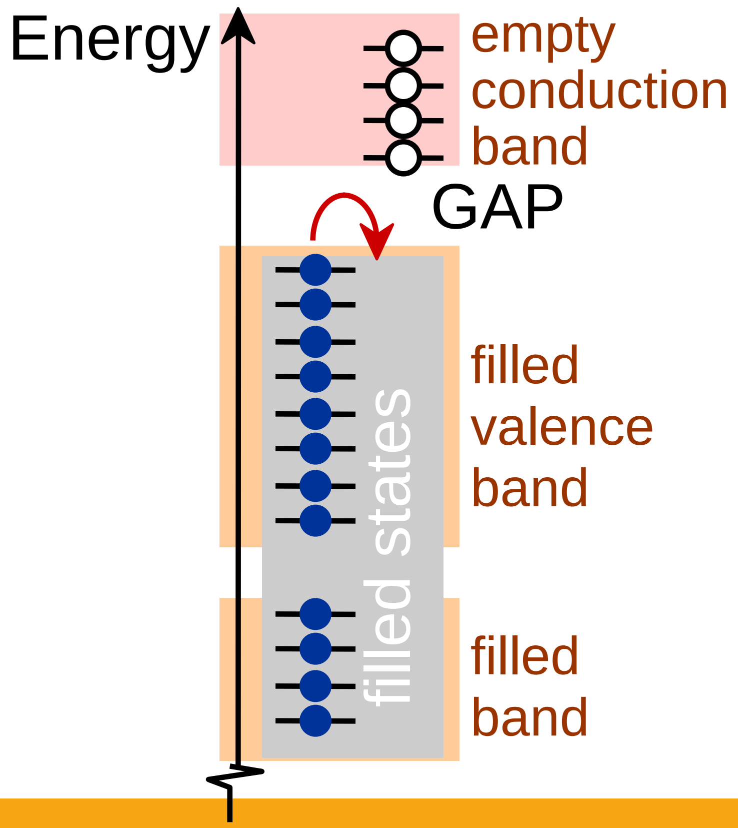


Table 12.4 Typical Room-Temperature Electrical Conductivities for 13 Nonmetallic Materials

Material	*Electrical Conductivity* $[(\Omega\text{-}m)^{-1}]$
Graphite	3×10^4–2×10^5
Ceramics	
Concrete (dry)	10^{-9}
Soda–lime glass	10^{-10}–10^{-11}
Porcelain	10^{-10}–10^{-12}
Borosilicate glass	$\sim 10^{-13}$
Aluminum oxide	$<10^{-13}$
Fused silica	$<10^{-18}$
Polymers	
Phenol-formaldehyde	10^{-9}–10^{-10}
Poly(methyl methacrylate)	$<10^{-12}$
Nylon 6,6	10^{-12}–10^{-13}
Polystyrene	$<10^{-14}$
Polyethylene	10^{-15}–10^{-17}
Polytetrafluoroethylene	$<10^{-17}$

Semiconductors

- In semiconductors, bonding is predominantly covalent (relatively weak).
- These electrons are more easily removed by thermal excitation.
- The band-gap is smaller, the valence band is full, and the conduction band is empty.

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

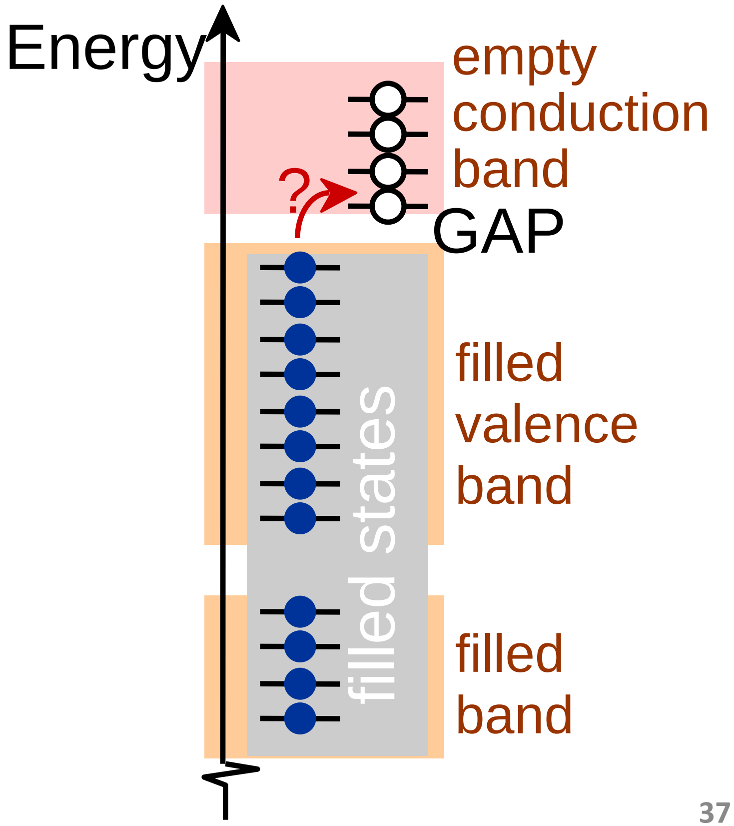
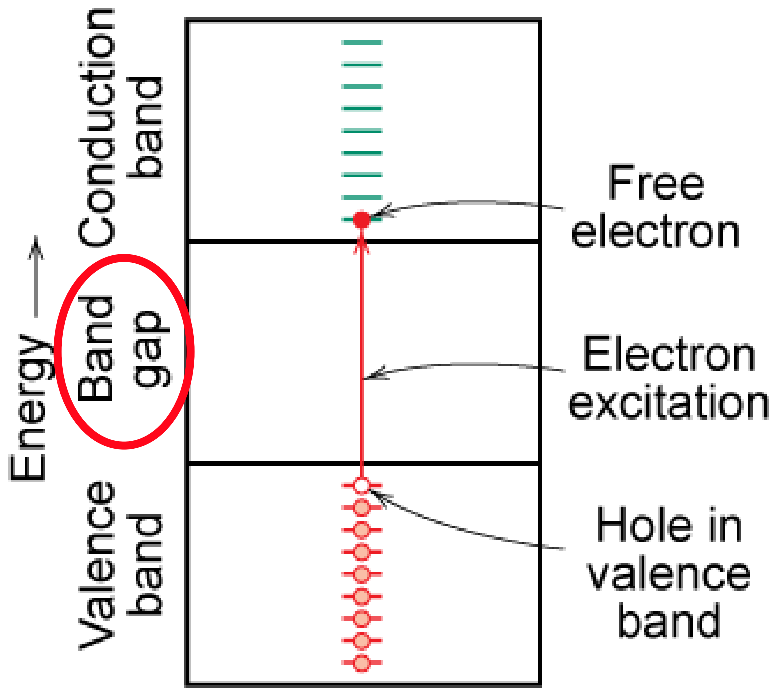


Table 12.3 **Band Gap Energies, Electron and Hole Mobilities, and Intrinsic Electrical Conductivities at Room Temperature for Semiconducting Materials**

Material	*Band Gap* (eV)	*Electrical Conductivity* $[(\Omega\text{-}m)^{-1}]$	*Electron Mobility* ($m^2/V\text{-}s$)	*Hole Mobility* ($m^2/V\text{-}s$)
		Elemental		
Si	1.11	4×10^{-4}	0.14	0.05
Ge	0.67	2.2	0.38	0.18
		III–V Compounds		
GaP	2.25	—	0.03	0.015
GaAs	1.42	10^{-6}	0.85	0.04
InSb	0.17	2×10^{4}	7.7	0.07
		II–VI Compounds		
CdS	2.40	—	0.03	—
ZnTe	2.26	—	0.03	0.01

Charge Carriers in Insulators and Semiconductors



Two types of electronic charge carriers:

Free Electron

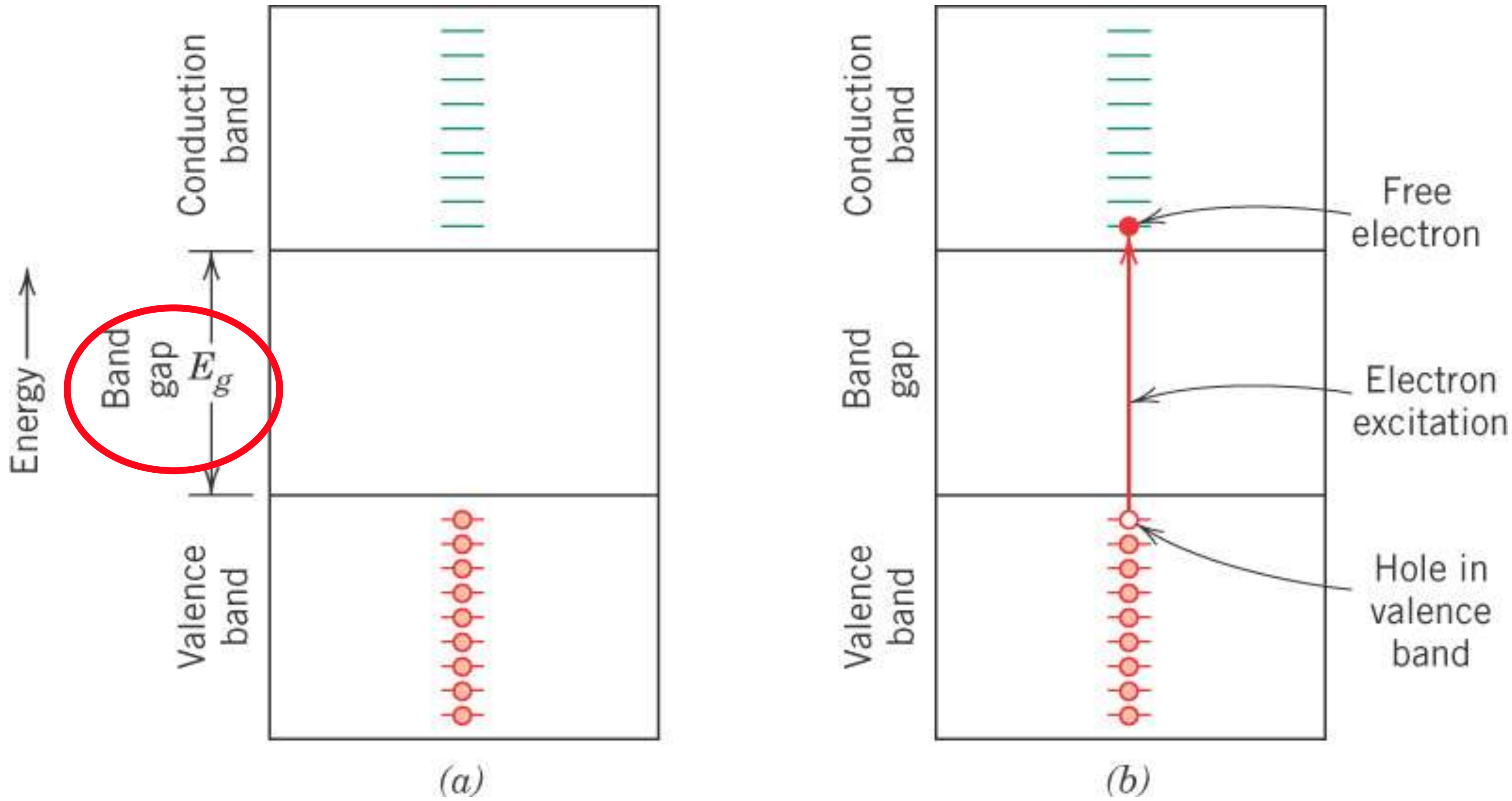
- negative charge
- located in conduction band
- energy level greater than E_f

Hole

- positive charge
- vacant electron state in the valence band

Move at different speeds - drift velocities

Free Electrons



Energy (E_g) required to promote electrons from the valence band to the conduction band.