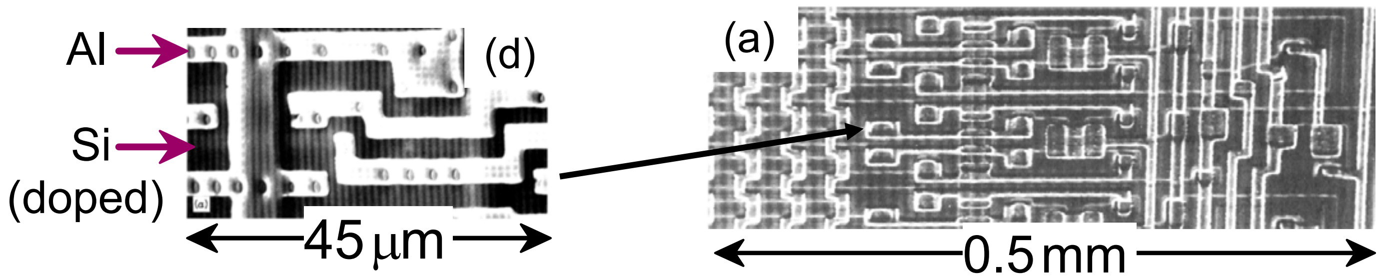
CHAPTER 18:
Electrical properties

ISSUES TO ADDRESS...

- How are electrical conductance and resistance characterized?
- What are the physical phenomena that distinguish conductors, semiconductors, and insulators?
- For metals, how is conductivity affected by imperfections, T, and deformation?
- For semiconductors, how is conductivity affected by impurities (doping) and T?

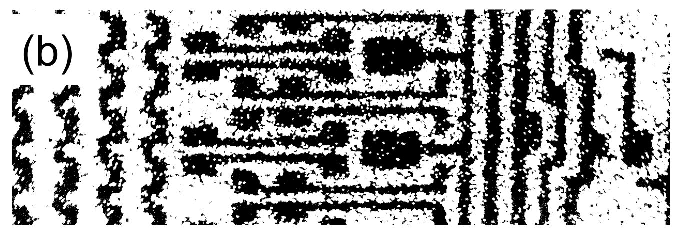
View of an integrated circuit

- Scanning electron microscope images 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.

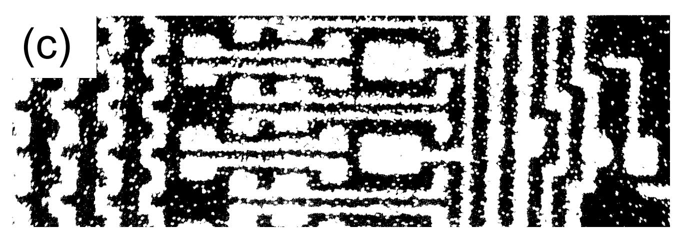


Fig. (d) from Fig. 18.25, *Callister 6e*. (Fig. 18.25 is courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

Fig. (a), (b), (c) from Fig. 18.0, *Callister 6e*.

Electrical conduction

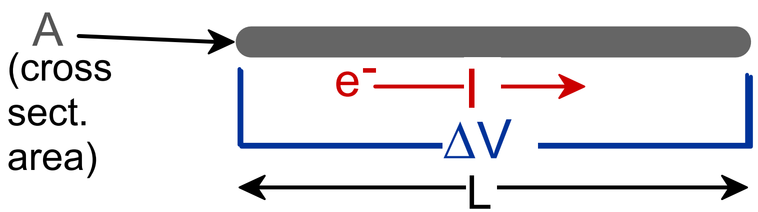
- Ohm's Law:

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

voltage drop (volts)

current (amps)

resistance (Ohms)



- Resistivity, ρ and Conductivity, σ:

--geometry-independent forms of Ohm's Law

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

E: electric field intensity

resistivity (Ohm-m)

J: current density

conductivity

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

- Resistance: $R = \dfrac{\rho L}{A} = \dfrac{L}{A\sigma}$

Conductivity: comparison

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

conductors

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

insulators

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}

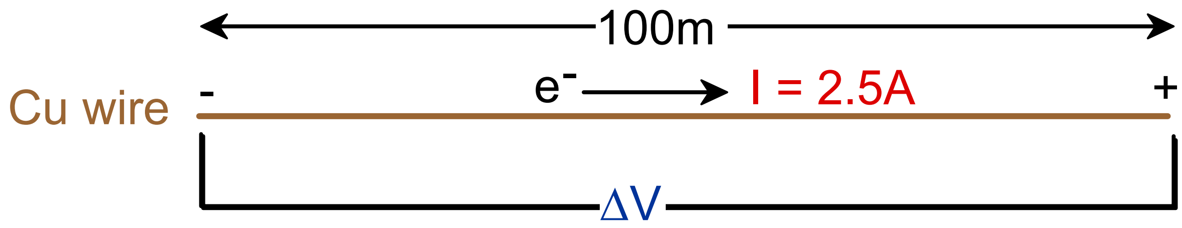
semiconductors

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

Selected values from Tables 18.1, 18.2, and 18.3, *Callister 6e*.

Ex: Conductivity problem

- Question 18.2, p. 649, *Callister 6e*:



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

$$R = \frac{L}{A\sigma} = \frac{\Delta V}{I}$$

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

Solve to get D > 1.88 mm

Electron mobility

Under acceleration from external electric field

- Average distance traveled by electrons = *mean free path, d*. The *drift velocity*, v_e is the average speed of the electrons.

$$v_d = d/t$$

The ***mobility*** is defined as

$$\mu_e = v_d/\mathrm{E} \text{ (expressed in } m^2/V.s)$$

Conductivity expression

In general, for an electronic carrier

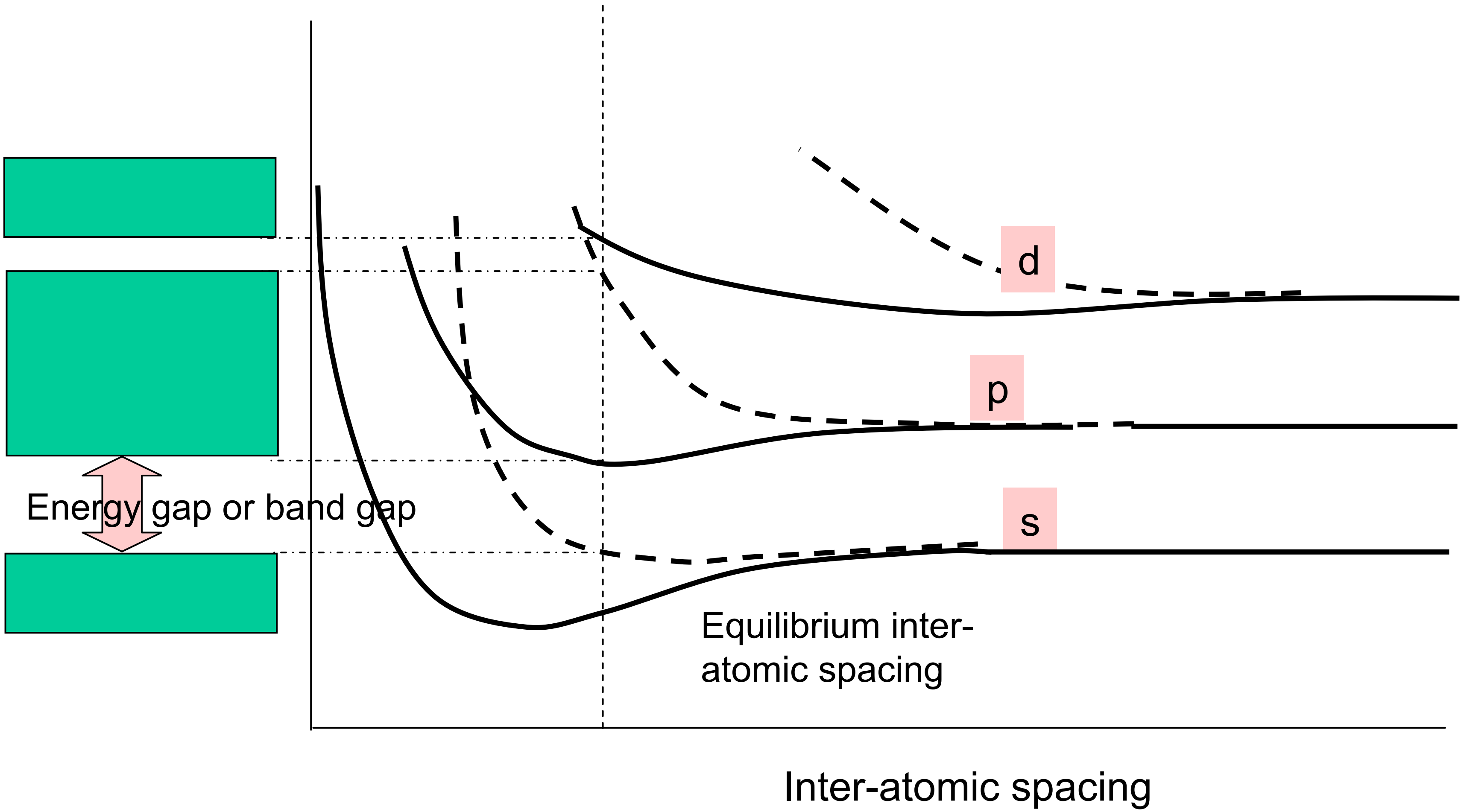
$$\sigma = n\, e\, \mu_e$$

n, the number of carriers per unit volume, or density of carriers (#carriers/m^3).

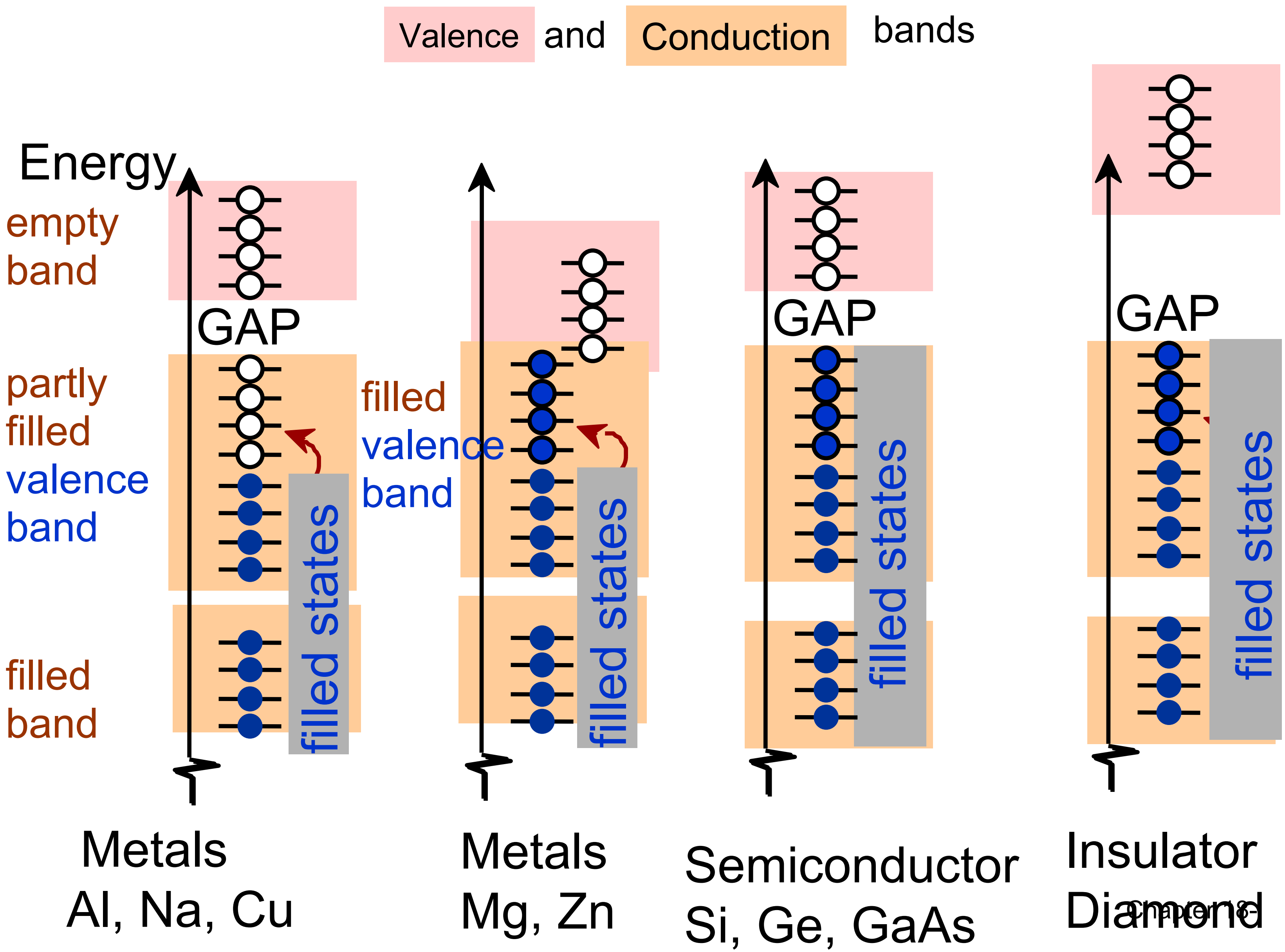
e, the electron charge, (1.6×10^{-19} Coulombs)

μ_e, the electron mobility, ($m^2/V.s$)

Energy Band model



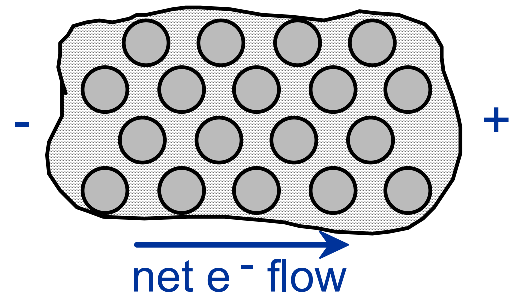
Energy band structures



Conduction & electron transport

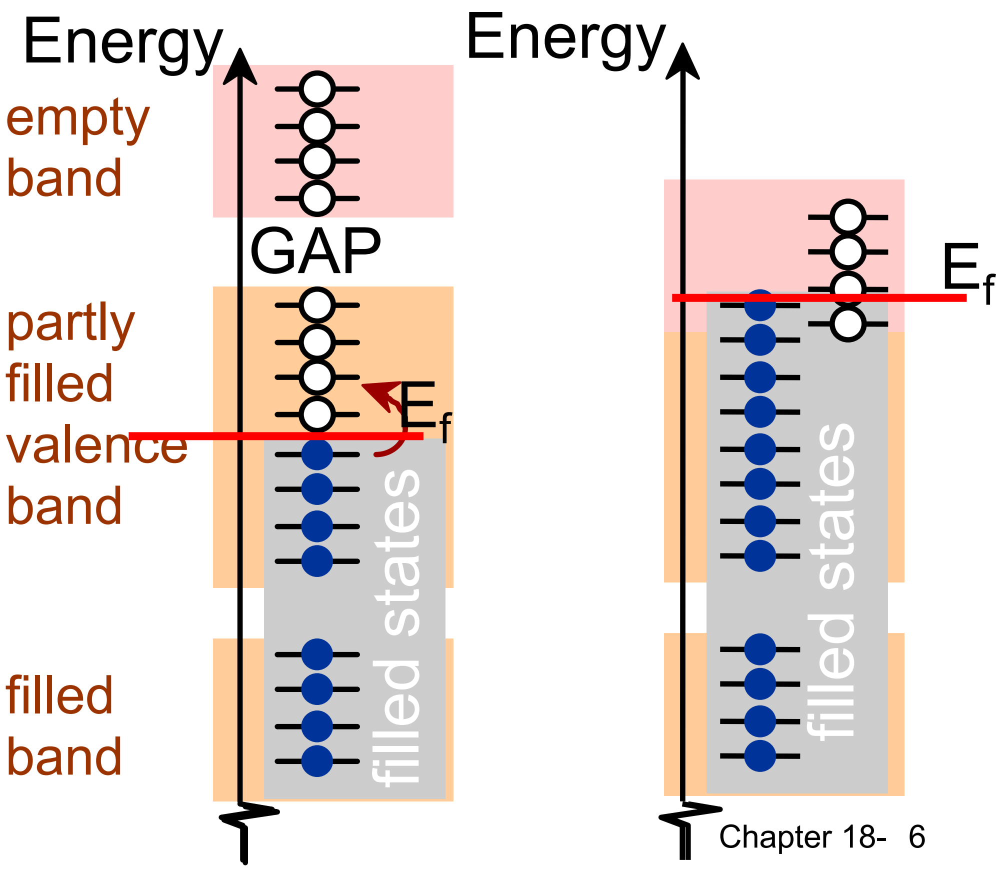
- Metals:

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



- Energy States:

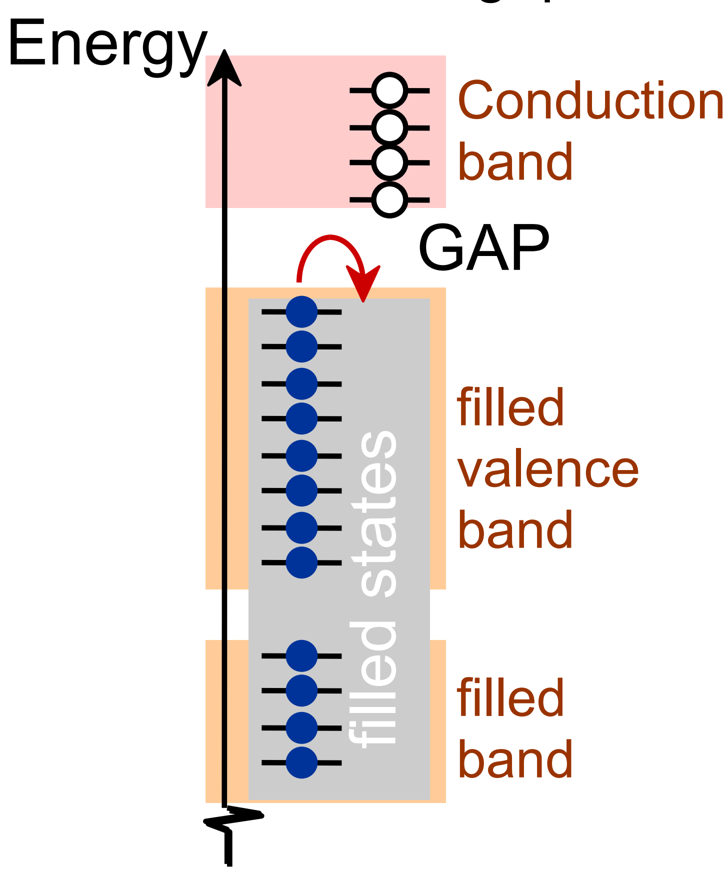
-- the cases below for metals show that nearby energy states are accessible by thermal fluctuations.



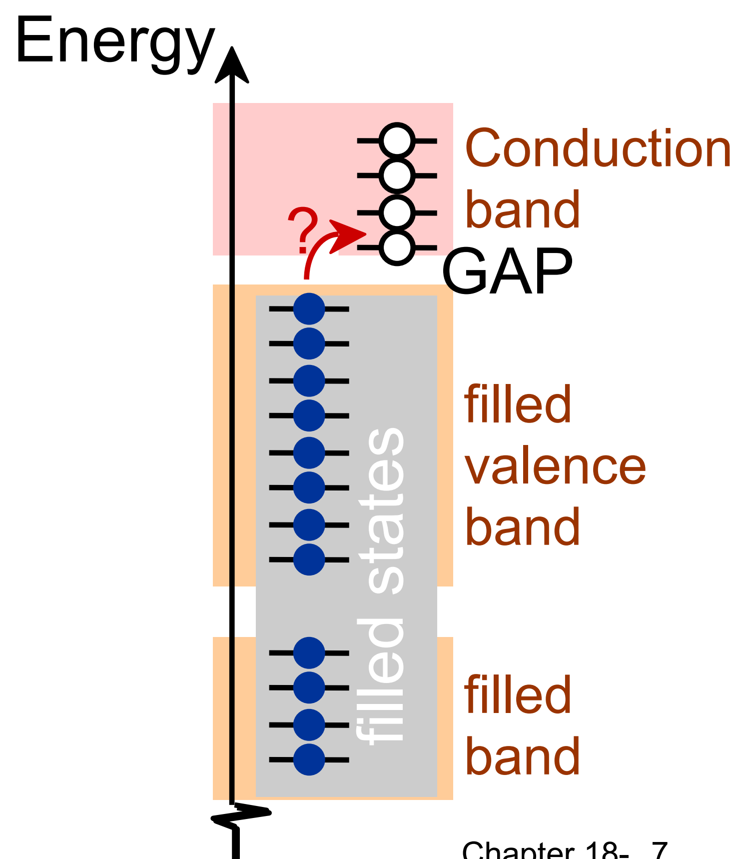
Fermi energy = energy corresponding to top most filled state at 0K

Energy states: insulators and semiconductors

- Insulators:
  --Higher energy states not accessible due to gap.



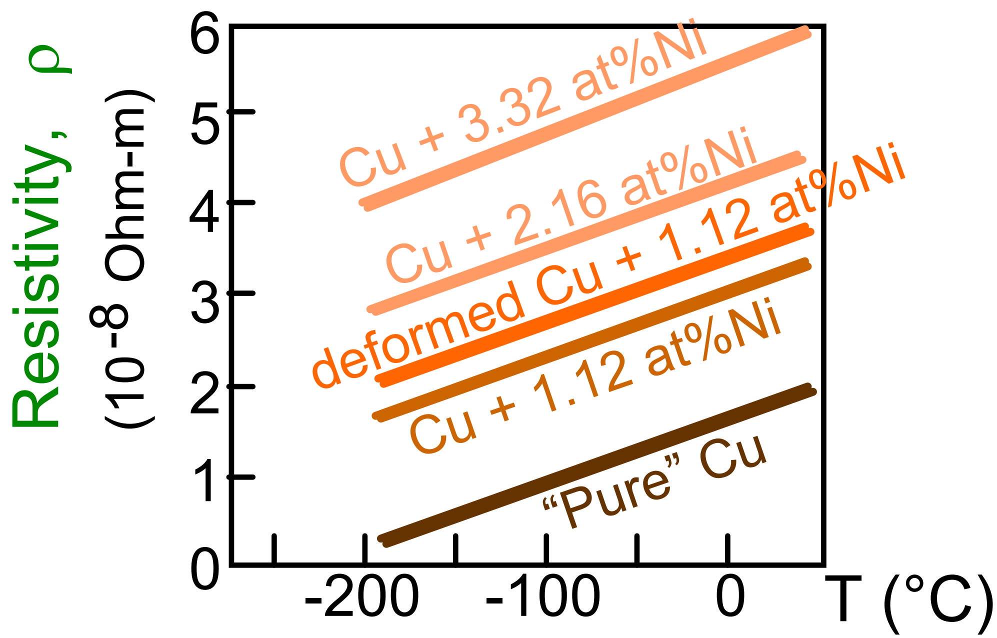
- Semiconductors:
  --Higher energy states separated by a smaller gap.



Metals: resistivity vs T, impurities

- Imperfections increase 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 6e*. (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.)

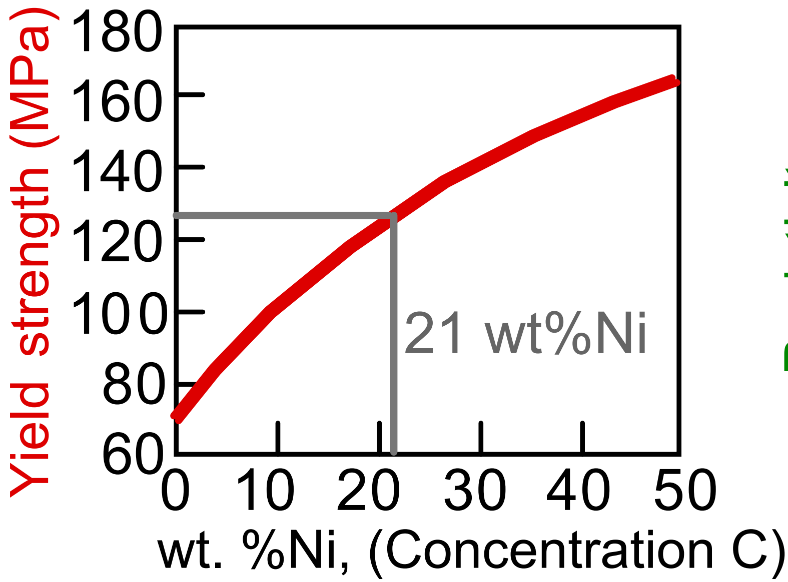
- Resistivity increases with:
  - --temperature
  - --wt% impurity
  - --%CW

$$\rho = \rho_{thermal} + \rho_{thermal} + \rho_{def}$$

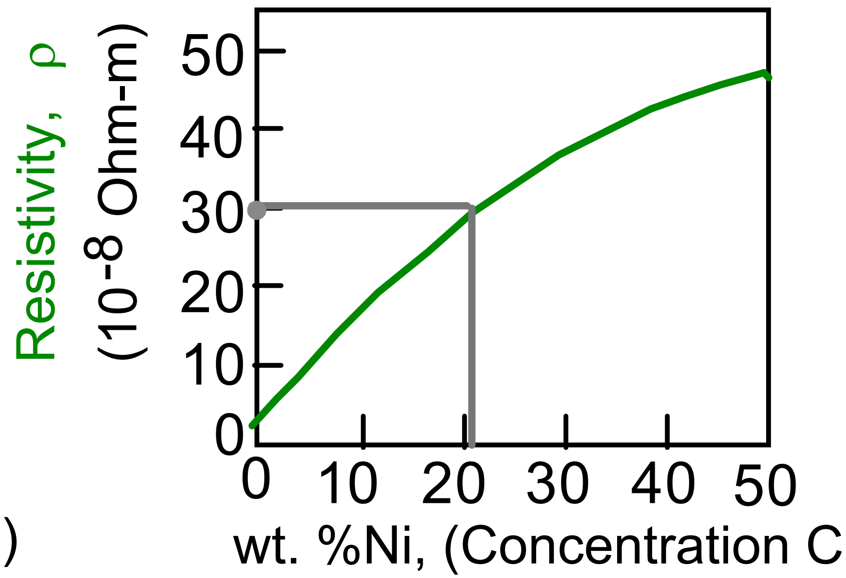
Ex: Estimating conductivity

- Question:

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



Adapted from Fig. 7.14(b), *Callister 6e*.

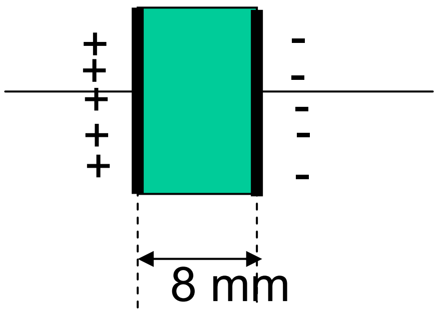


Adapted from Fig. 18.9, *Callister 6e*.

$$\rho = 30\text{x}10^{-8} \text{ Ohm} - \text{m}$$

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

Energies



Electrical energy

Voltage gradient or electric field
1.25×10^{6} volts/cm ~ 2.5 eV

Thermal energy

Average thermal energy = kT
At RT (~300 K) = 0.86 x 300 = 0.026 eV
At 2000 C, kT = measily 0.2 eV

Light energy

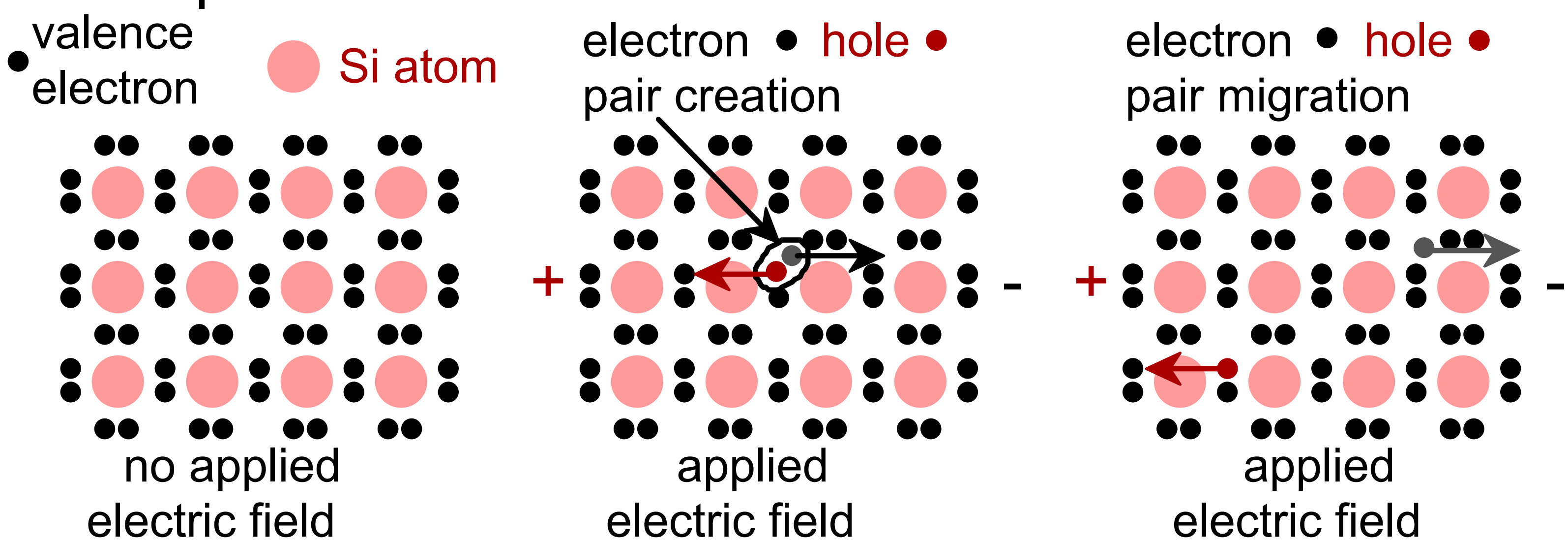
Visible light photon energy quanta whooping 1.7 to 3.1 eV!

Shining light of a given wavelength on a crystal transfer more electrons across the gap than through thermal excitation or electric field!!!.

Obviously Light carries lots of energy!!!!

Conduction in terms of electron and hole migration

- Concept of electrons and holes:



Adapted from Fig. 18.10, *Callister 6e*.

- Electrical Conductivity given by:

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

holes/m^3 (p); hole mobility (μ_h); # electrons/m^3 (n); electron mobility (μ_e)

Intrinsic vs extrinsic conduction

- **Intrinsic**:

  \# electrons = # holes (n = p)

  --case for pure Si

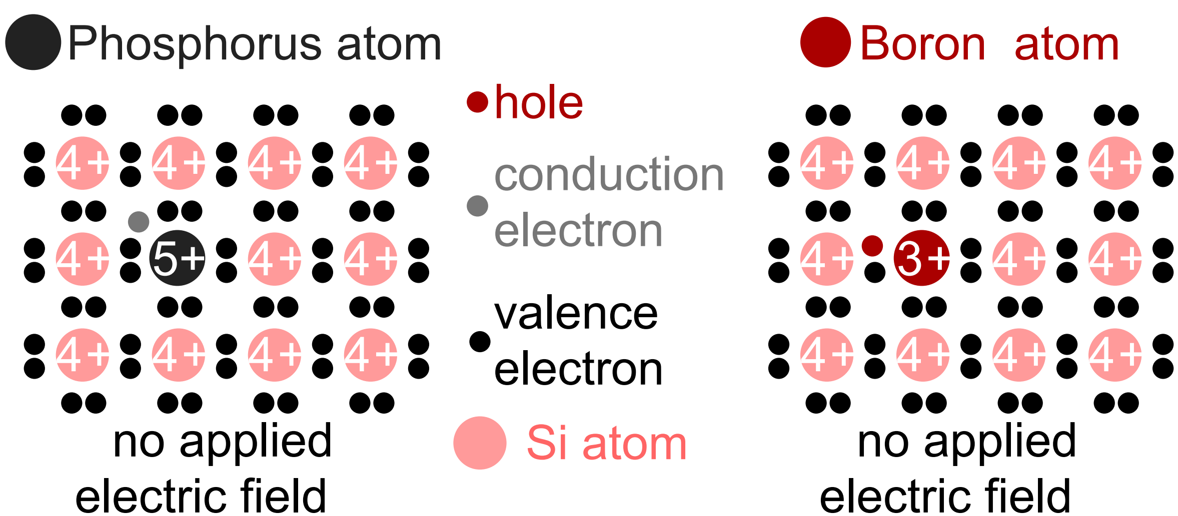
- **Extrinsic**:

  --n ≠ p

  --occurs when impurities are added with a different # valence electrons than the host (e.g., Si atoms)

- N-type Extrinsic: (n >> p)
- P-type Extrinsic: (p >> n)

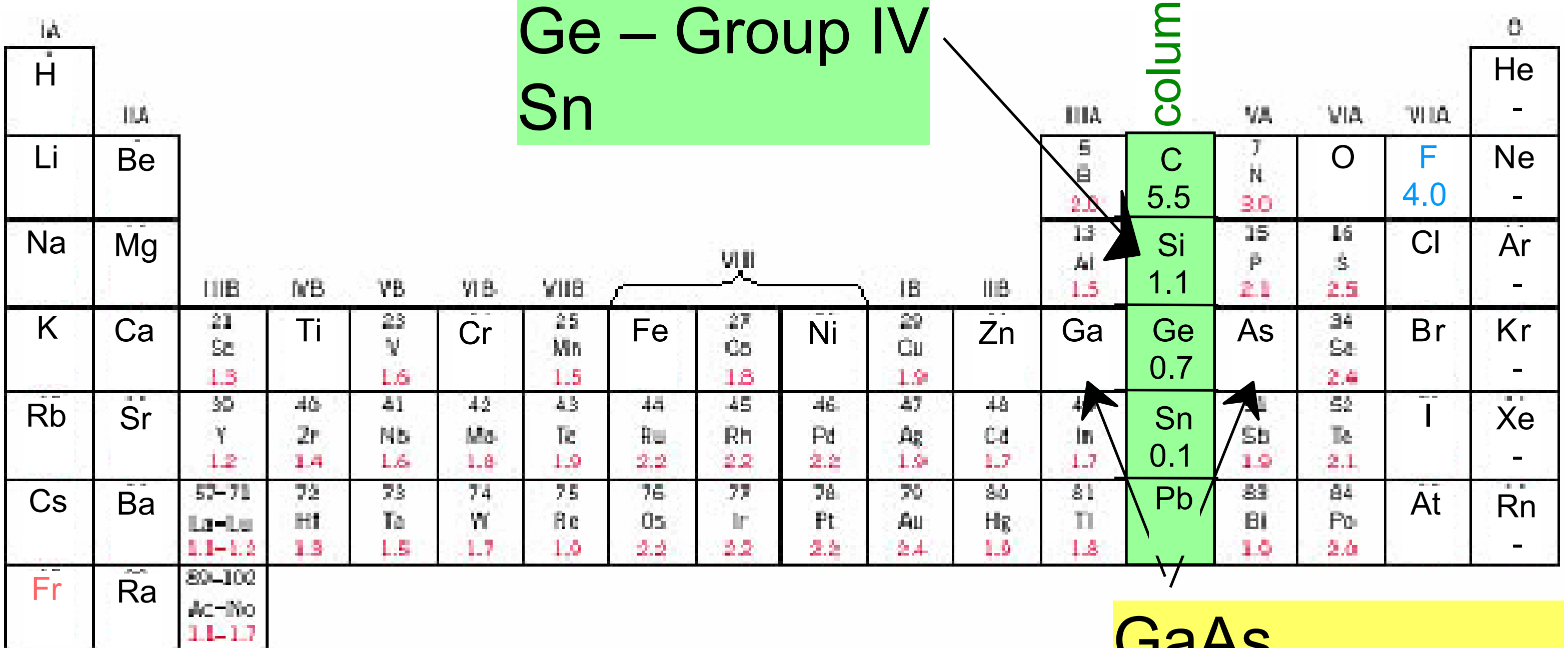
$\sigma \approx n|e|\mu_e$



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

Examples of elemental and compound semiconductors

Si
Ge – Group IV
Sn



1940, 3rd edition. Copyright 1960 by Cornell University.

GaAs
GaP – Group III-V
CdS

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

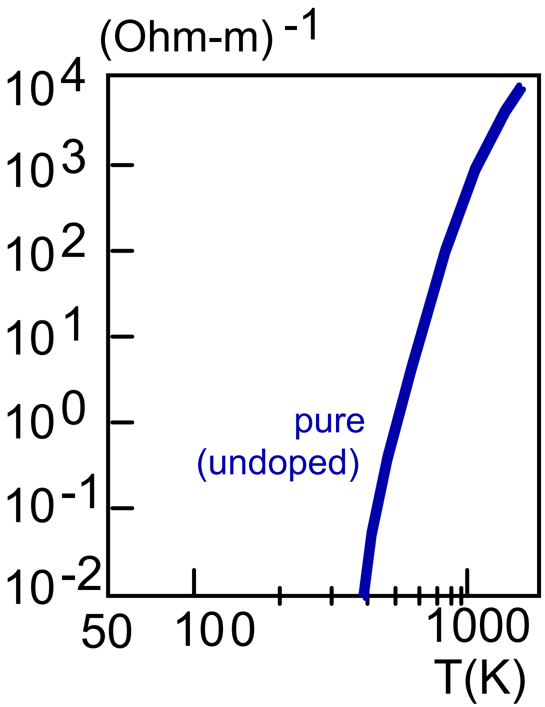
ZnSe
CdTe – Group II-VI
HgTe

Pure semiconductors: conductivity vs T

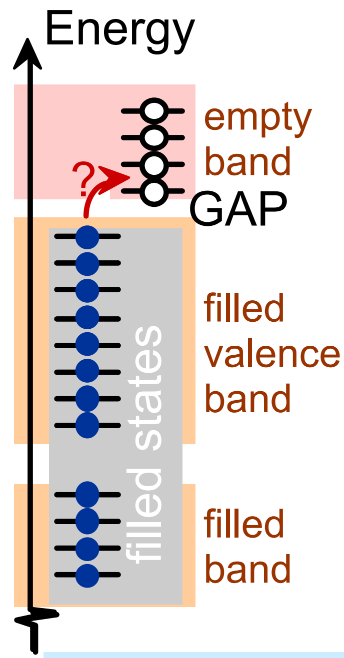
- Data for Pure Silicon:
  - --σ increases with T
  - --opposite to metals

$$\sigma_{undoped} \propto e^{-E_{gap}/2k_B T}$$

electrical conductivity, σ



Adapted from Fig. 19.15, *Callister 5e*. (Fig. 19.15 adapted from G.L. Pearson and J. Bardeen, *Phys. Rev.* **75**, p. 865, 1949.)



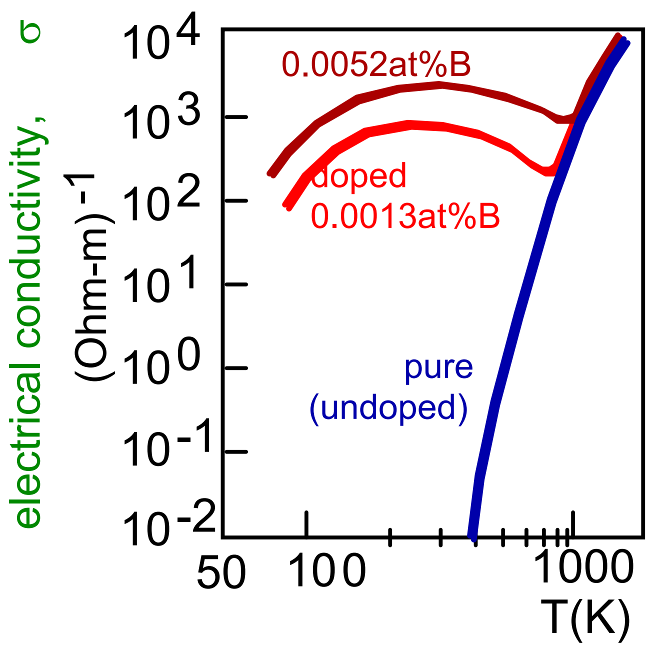
electrons can cross gap at higher T

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

Selected values from Table 18.2, *Callister 6e*.

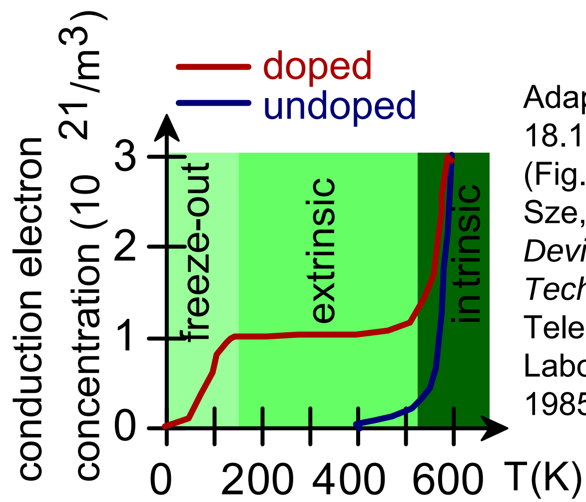
doped semicon: conductivity vs T

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



Adapted from Fig. 19.15, *Callister 5e*. (Fig. 19.15 adapted from G.L. Pearson and J. Bardeen, *Phys. Rev.* **75**, p. 865, 1949.)

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

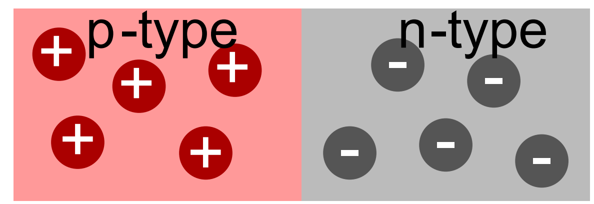


Adapted from Fig. 18.16, *Callister 6e*. (Fig. 18.16 from S.M. Sze, *Semiconductor Devices, Physics, and Technology*, Bell Telephone Laboratories, Inc., 1985.)

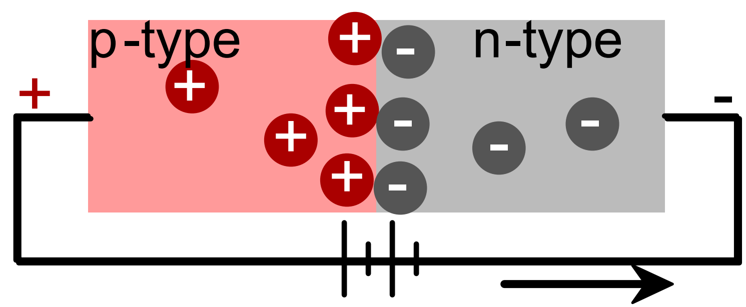
P-N rectifying junction

- 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.
- Results:

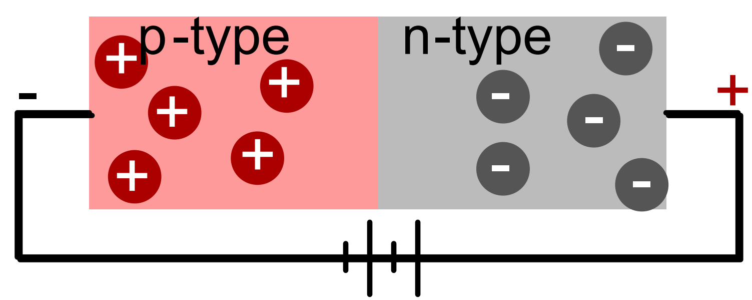
--No applied potential:
no net current flow.



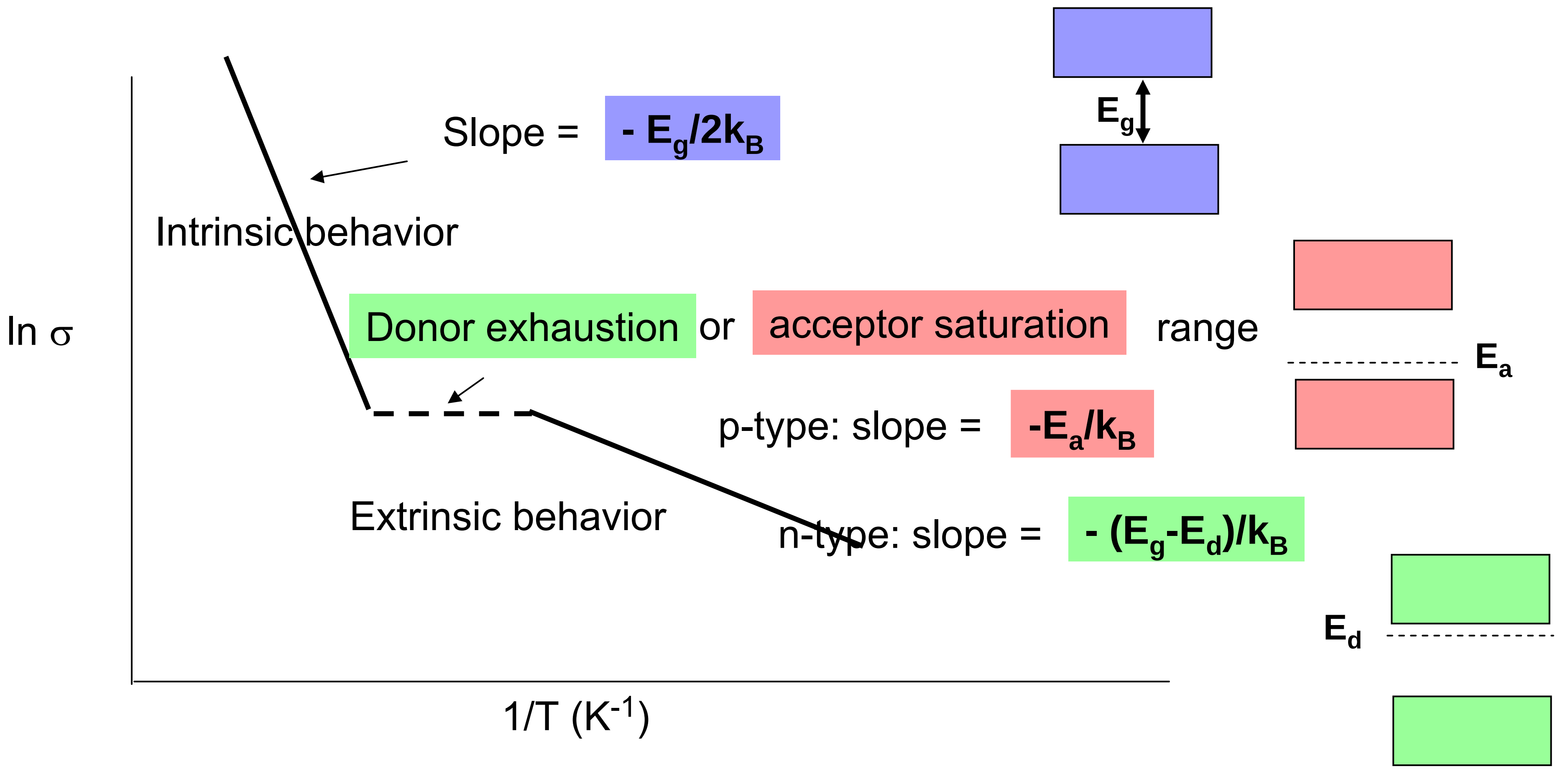
--Forward bias: carrier flow through p-type and n-type regions; holes and electrons recombine at p-n junction; current flows.



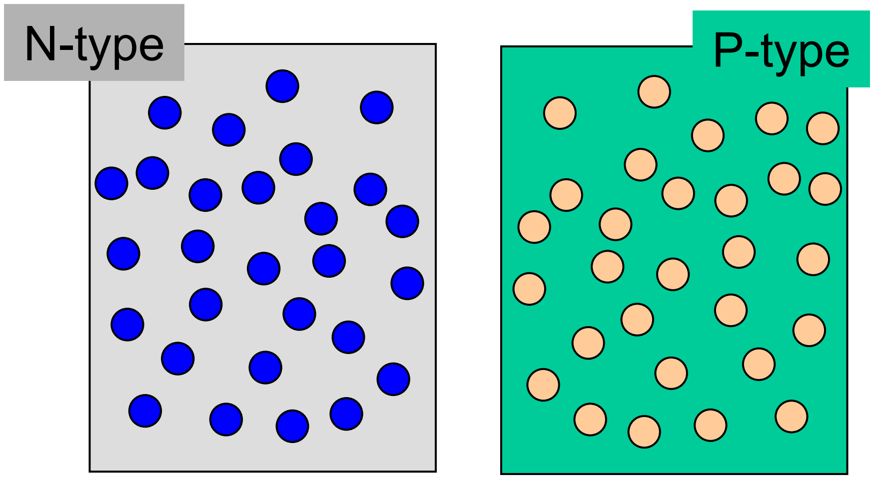
--Reverse bias: carrier flow away from p-n junction; carrier conc. greatly reduced at junction; little current flow.



Extrinsic – Intrinsic temperature behavior



Silicon solar cell, E_g = 1.1 eV

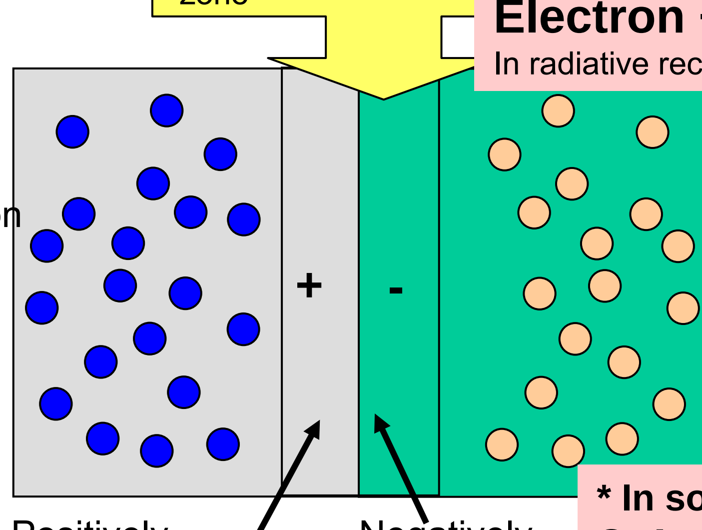


On contact electrons and holes neutralize each other in A thin layer recombination zone

Electron + hole = hν

In radiative recombination*

Charge separation creates electric field

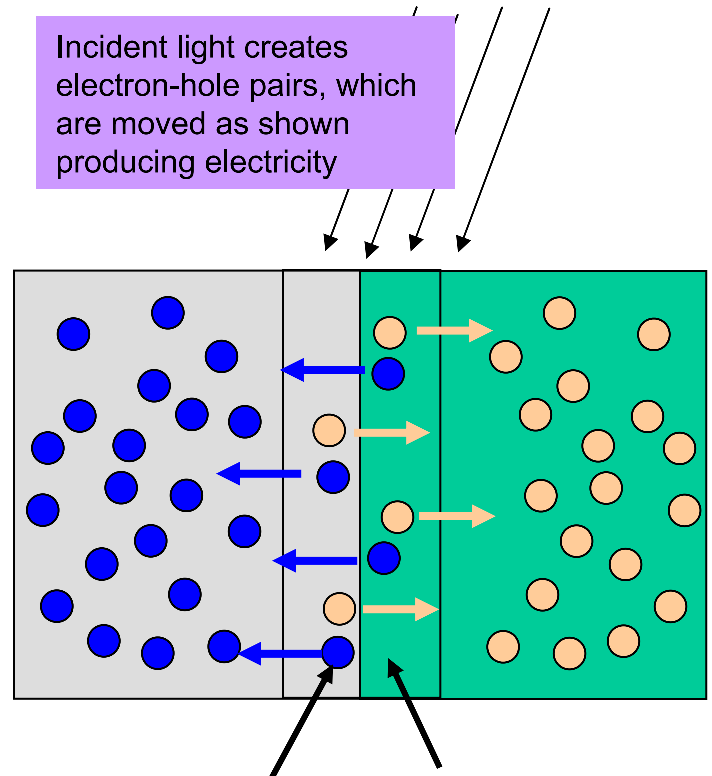


Positively charged layer

Negatively charged layer

hν = Electron + hole

Incident light creates electron-hole pairs, which are moved as shown producing electricity

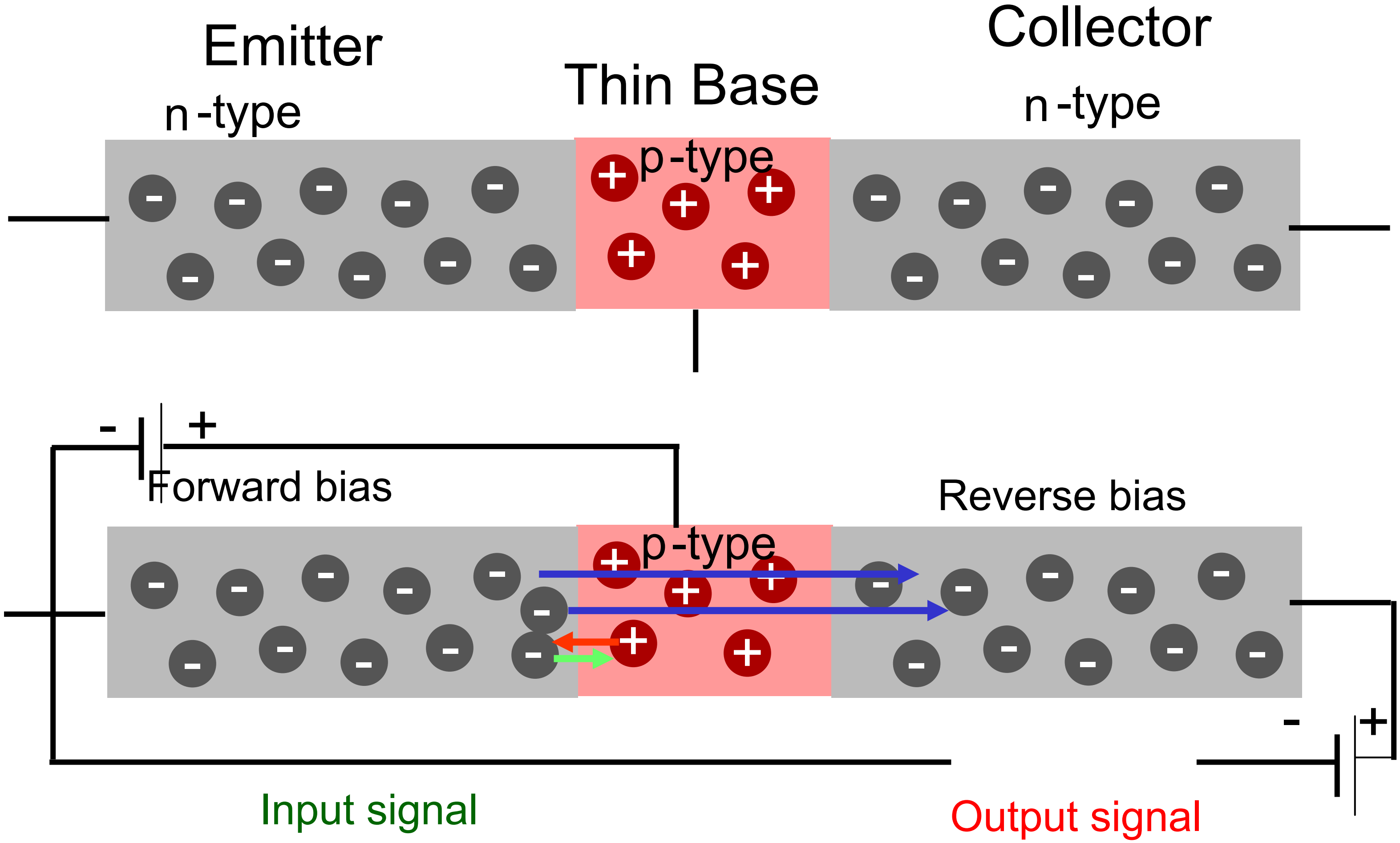


Positively charged layer

Negatively charged layer

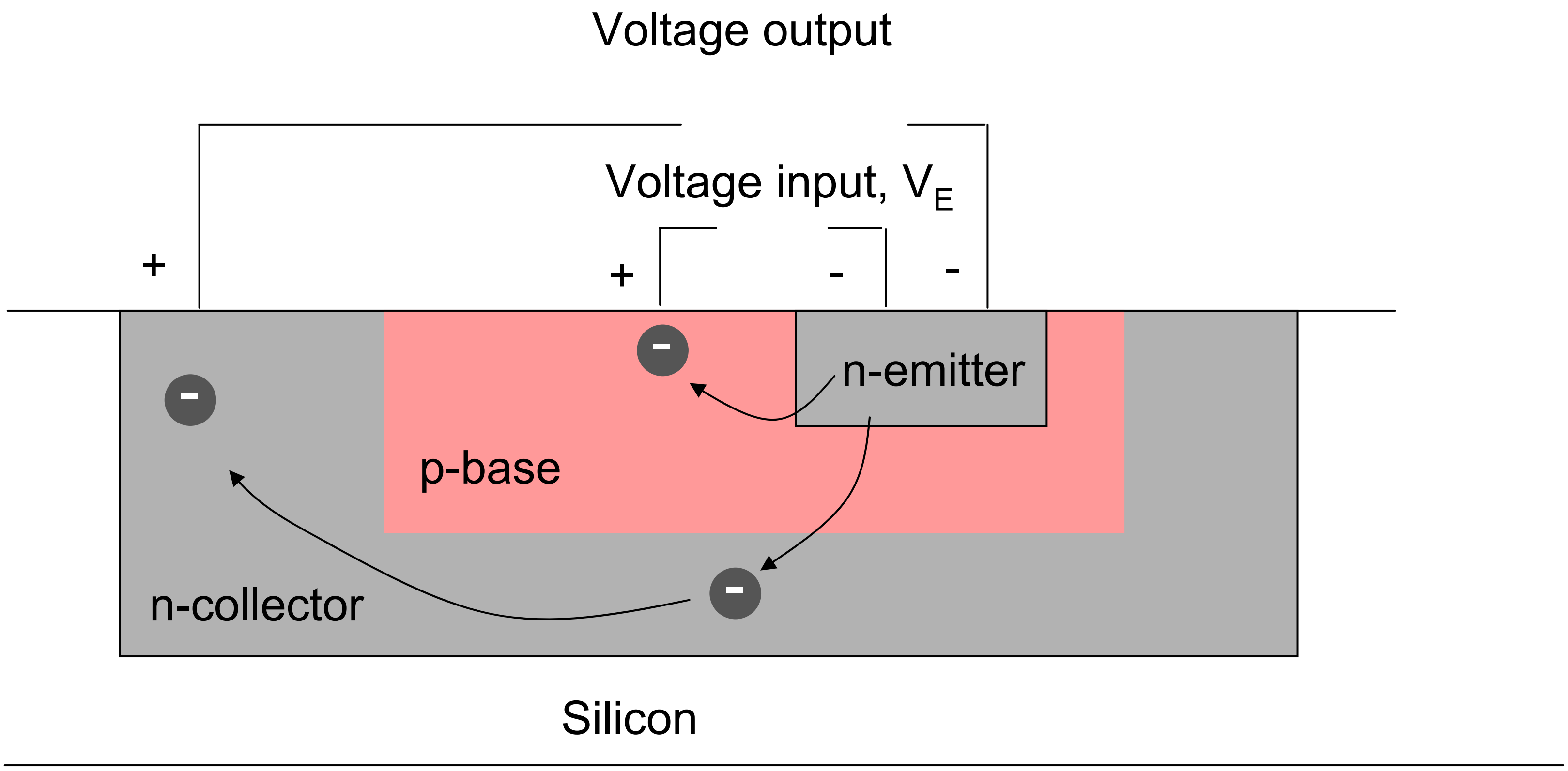
*** In some materials, such as GaAs, GaN light is given off**

Transistors



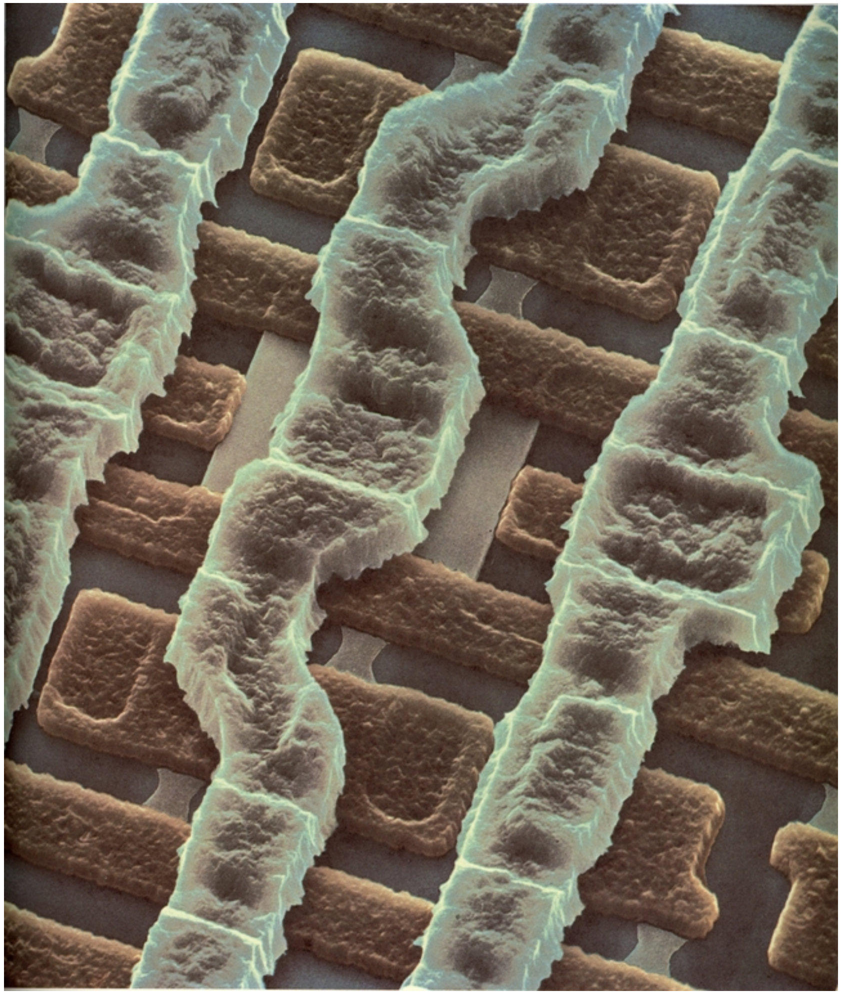
Recombination

Bipolar junction transistor



SUMMARY

- Electrical conductivity and resistivity are:
  --material parameters.
  --geometry independent.
- Electrical resistance is:
  --a geometry and material dependent parameter.
- Conductors, semiconductors, and insulators...
  --different in whether there are accessible energy states for conductance electrons.
- For metals, conductivity is increased by
  --reducing deformation
  --reducing imperfections
  --decreasing temperature.
- For pure semiconductors, conductivity is increased by
  --increasing temperature
  --doping (e.g., adding B to Si (p-type) or P to Si (n-type).



ANNOUNCEMENTS

Reading: Chapter 18 1-13

Core Problems: Chapter 18: 7, 12, 29,

Self-help Problems: Design Example 18.1