ELECTRICAL PROPERTIES

OUTLINE

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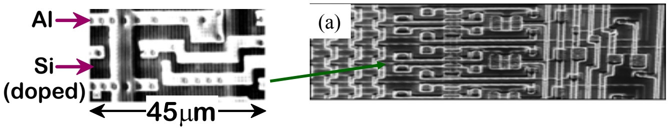
- INSULATORS AND SEMICONDUCTORS
- METALS: *ELECTRON MOBILITY*
- INFLUENCE OF TEMPERATURE
- INFLUENCE OF IMPURITY
- SEMICONDUCTORS
- P-N RECTIFYING JUNCTION
- SUMMARY

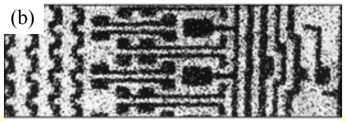
INTRODUCTION

- Scanning electron microscope images of an IC:

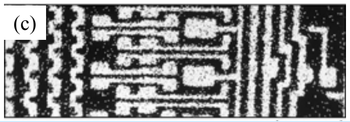


From Fig. 18.0 and 18.25 *Callister 6e.*

- In SEM the electron beam causes the surface atoms to emit X-rays.
- It is possible to filter all the rays but the ones from the atom of interest.
- When these rays are projected on a cathode tube screen, they will generate white dots – *dot map*



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

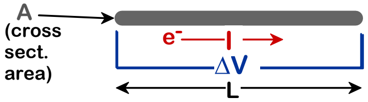


A dot map showing location of Al (a conductor).
- Al shows up as light regions.

ELECTRICAL CONDUCTION

- Ohm's Law:

R depends on specimen geometry



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

voltage drop (volts)

current (amps)

resistance (Ohms)

- Resistivity, ρ and Conductivity, σ:

→ geometry-independent forms of Ohm's Law

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

Elelectric Field intensity

resistivity (Ohm-m)

J: current density

Conductivity:

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

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

CONDUCTIVITY: *COMPARISON*

- solid materials exhibit a very wide range of electrical conductivity

– ……… *range compared to other phys. properties.*

→ *Materials can be classified according to their electrical conductivity.*

Conductivity values (Ohm-m)$^{-1}$ at room temp.

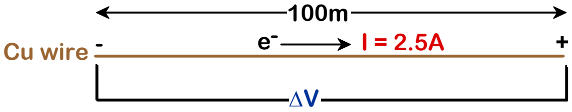
METALS	conductors	CERAMICS	
Silver	6.8×10^{7}	Soda-lime glass	10^{-10}
Copper	6.0×10^{7}	Concrete	10^{-9}
Iron	1.0×10^{7}	Aluminum oxide	$<10^{-13}$

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, 18.2, and 18.3, *Callister 6e.*

EXAMPLE

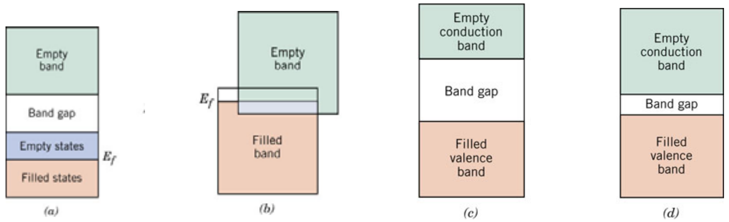
A copper wire 100 m long must experience a voltage drop of less than 1.5 V when a current of 2.5 A passes through it. If σ is 6.07×10^7 $(\text{Ohm-m})^{-1}$, compute the minimum diameter of the wire.



Energy Band Structure in Solids

The electrical properties of a solid material are a consequence of its ………… …………… : *the arrangement of the outermost electron bands and the way in which they are filled with electrons.*

The various possible electron band structures in solids at 0 K:



From Fig. 18.4 Callister 8th. ed.

metals such as copper, in which electron states are available above and adjacent to filled states, in the same band.

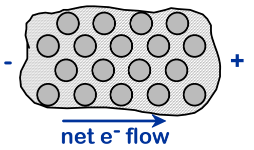
The electron band structure of metals such as magnesium, wherein there is an ………. of filled and empty outer bands.

Insulators: the filled valence band is separated from the empty conduction band by a relatively ………. band gap (2 eV).

Semiconductors: same as for insulators except that the band gap is relatively ……….. (2 eV).

CONDUCTION & ELECTRON TRANSPORT

- Only electrons with energies greater than the Fermi energy E_f (i.e. free electrons) may be acted on and accelerated when the electric field is applied.
  - Holes have energies less than E_f and also participate in electronic conduction.
  - The electrical conductivity depends on the **numbers** of ……………. and …………..

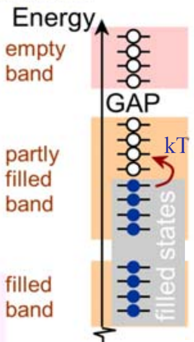


Electron sea in metals

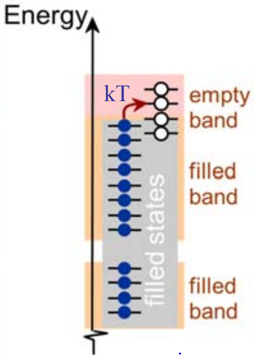
- Metals:
- Thermal energy (kT) puts many electrons into a higher energy state.

- Energy States:
- for metals the nearby energy states are accessible by thermal fluctuations.

Free electrons are different from the electron sea! They do not become truly free until they have the required excitation ($E>E_f$)



e.g. copper



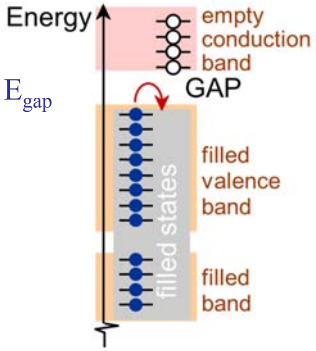
e.g. magnesium

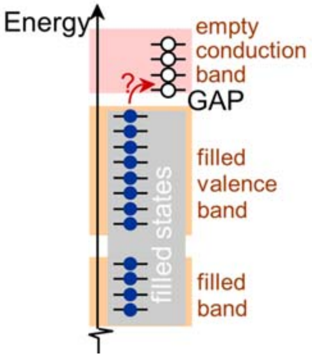
INSULATORS AND SEMICONDUCTORS

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

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

$kT < E_{gap}$



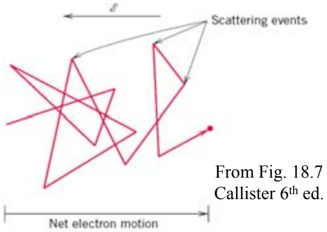


The …….. the band gap, the ……… is the electrical conductivity at a given temp.

METALS: *Electron Mobility*

- Imperfections ………. resistivity
  - grain boundaries
  - dislocations
  - impurity atoms
  - vacancies

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



From Fig. 18.7 Callister 6th ed.

- Resistivity **increases** with temp., impurity concentration and %CW

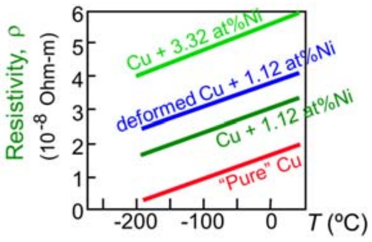
$$\rho_{total} = \rho_{thermal} + \rho_{impurity} + \rho_{def}$$

$$\rho_{thermal} = \rho_o + aT$$ ………….. rule

Where ρ_o and a are constants for each metal.

T ↑ → vibration and lattice defects ↑ → electron scattering ↑

%CW ↑ → dislocation concentration ↑ → resistivity ↑



Adapted from Fig. 18.8, *Callister 6e*.

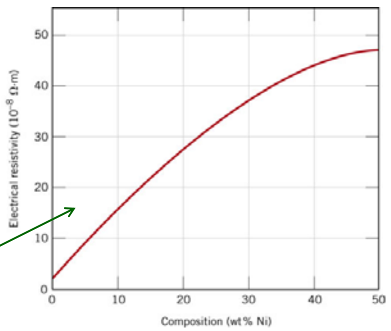
INFLUENCE OF IMPURITY

$$\rho_{total} = \rho_{thermal} + \rho_{impurity} + \rho_{def}$$

$$\rho_{impurity} = Ac_i(1-c_i)$$

Where c_i is impurity concentration in atomic % and A is constant.

Ni atoms scatter the electrons → ρ ↑



The effect of Ni impurity additions on the room temp. resistivity of Cu.

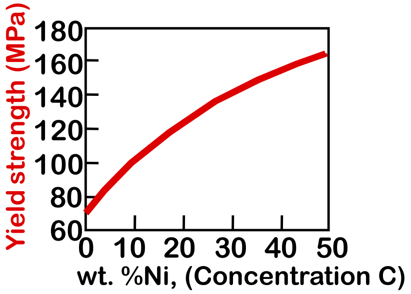
For a two phase alloy a rule of mixtures applies and the impurity reisistivity can be estimated as:

$$\rho_{impurity} = \rho_\alpha V_\alpha + \rho_\beta V_\beta$$

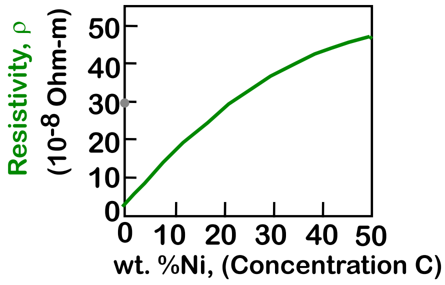
V's and ρ's are the volume fraction and individual resistivities for each phase.

EXAMPLE

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



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



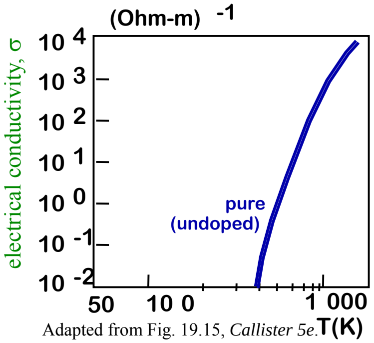
Adapted from Fig. 18.9, *Callister 6e*.

SEMICONDUCTORS

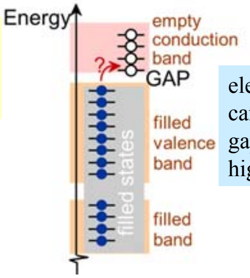
- Pure "………" Silicon:
  - T ↑ → σ ↑
  - **opposite** to metals

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

For every electron excited into the conduction band there is left behind a missing electron - ………



Adapted from Fig. 19.15, *Callister 5e*.



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*.

ELECTRON AND HOLE MIGRATION

- Electrical Conductivity given by:

holes/m³

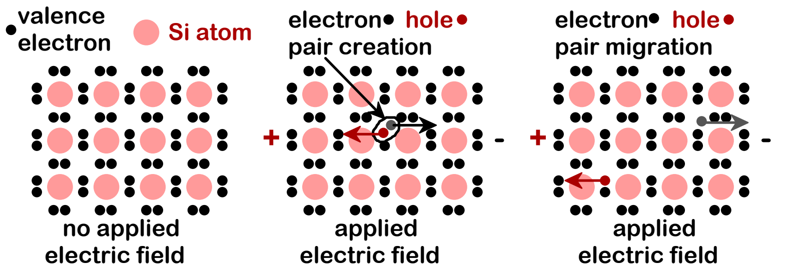
$$\sigma = n|e|\mu_e + p|e|\mu_h$$

hole mobility

electrons/m³

electron mobility

In intrinsic semi-conductors n|e = p|e



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

INTRINSIC VS EXTRINSIC CONDUCTION

Intrinsic:

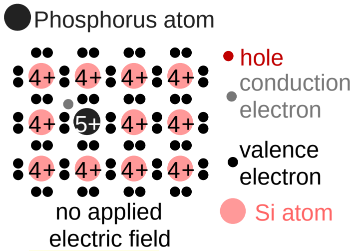
electrons = # holes (n = p)

- example pure Si or Ge

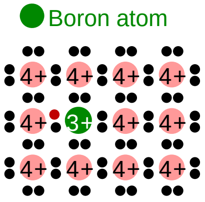
Extrinsic:

- n ≠ p
- occurs when impurities are added with a different # valence electrons than the host (*e.g., doping Si with P or B*)

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



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

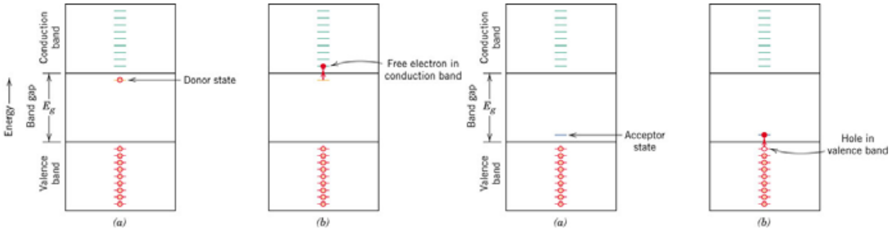


$$\sigma \approx p|e|\mu_h$$

INTRINSIC VS EXTRINSIC CONDUCTION

Donor impurities → **n-type** *(negative)* conductivity: by …………

Acceptor impurities → **p-type** *(positive)* conductivity: by ……….



(*a*) Donor impurity energy level located just below the bottom of the conduction band. (*b*) Excitation from a donor state in which a free electron is generated in the conduction band.

(*a*) Acceptor impurity level just above the top of the valence band. (*b*) Excitation of an electron into the acceptor level, leaving behind a hole in the valence band.

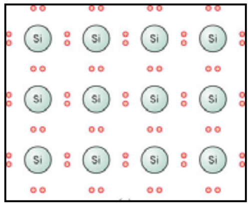
- ☐ Can control **concentration** of donors/acceptors ⇒ concentration of charge carriers ⇒ control conductivity
- Materials with desired conductivities can be manufactured

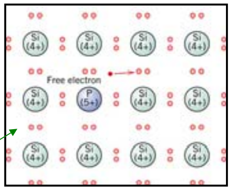
Semiconductors: Summary

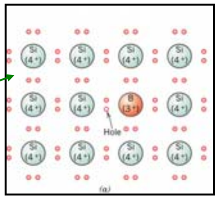
- ▪ Intrinsic conductivity (pure materials): electron-hole pairs
- Conductivity: Si 4×10^{-4} $(\Omega m)^{-1}$ vs. Fe 1×10^{7} $(\Omega m)^{-1}$
- Electron has to overcome the energy gap E_g

Intrinsic conductivity strongly depends on temperature and as-present impurities

- Extrinsic Conductivity
- Doping: substituting a Si atom in the lattice by an impurity atom (*……….*) that has one extra or one fewer valence electrons
- Donor impurities have one extra electron (*group V: P, As, Sb*), donate an electron to Si.
- Acceptor impurities have one fewer electrons (*group III: B, Al, In, Ga*), accept electrons from Si which creates holes.

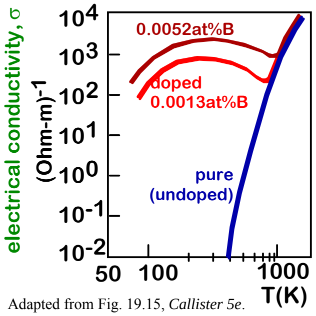




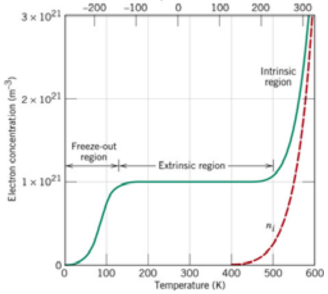


CONDUCTIVITY VS T FOR EXTRINSIC SEMICOND.

- Doped Silicon:
  - Dopant concentration ↑ - σ ↑
  - Reason: imperfection sites **lower** the activation energy to produce mobile electrons.



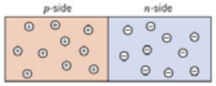
Adapted from Fig. 19.15, *Callister 5e.*



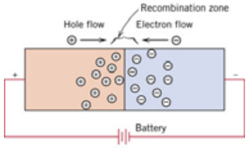
Adapted from Fig. 18.16, *Callister 6e.*

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

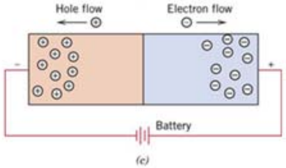
P-N RECTIFYING JUNCTION



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.

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

SUMMARY

- Electrical resistance is:
  - a geometry and material dependent parameter.
- Electrical conductivity and resistivity are:
  - material parameters and geometry independent.
- Conductors, semiconductors, and insulators...
  - different in whether there are accessible energy states for 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).

Next time:

Thermal Properties