Chapter 18: Electrical Properties

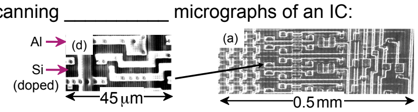
ISSUES TO ADDRESS...

- How are electrical conductance and resistance characterized?
- What are the physical phenomena that distinguish ___________________________________?
- For metals, how is _______________ affected by _______________________ and deformation?
- For semiconductors, how is conductivity affected by impurities (doping) and temperature?

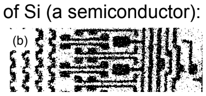
Chapter 18 - 1

View of an Integrated Circuit

- Scanning _________ micrographs of an IC:



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



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

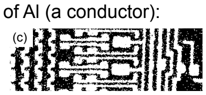


Fig. (d) from Fig. 12.27(a), *Callister & Rethwisch 3e.* (Fig. 12.27 is courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

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

Chapter 18 - 2

Electrical Conduction

- _________ Law: $V = I R$
  - voltage drop (volts = J/C), C = __________
  - current (amps = C/s)
  - resistance (Ohms)
- _______________, ρ:
  - -- a material property that is independent of sample size and geometry

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

A: surface area of current flow; ℓ: current flow path length

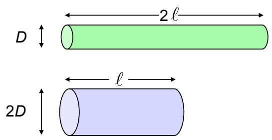
- _______________, σ

____

Chapter 18 - 3

Electrical Properties

- Which will have the greater ____________?



$$R_1 = \frac{2\rho\ell}{\pi\left(\frac{D}{2}\right)^2} = \frac{8\rho\ell}{\pi D^2}$$

$$R_2 = \frac{\rho\ell}{\pi\left(\frac{2D}{2}\right)^2} = \frac{\rho\ell}{\pi D^2} = \frac{R_1}{8}$$

- Analogous to flow of water in a pipe
- __________ depends on sample geometry and size.

Chapter 18 - 4

Definitions

Further definitions

[_______] <= another way to state Ohm's law

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

$\varepsilon \equiv$ ________________________________

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

Electron flux   conductivity   ____________

Chapter 18 - 5

Conductivity: Comparison

- Room temperature values (Ohm-m)$^{-1}$ = (Ω - m)$^{-1}$

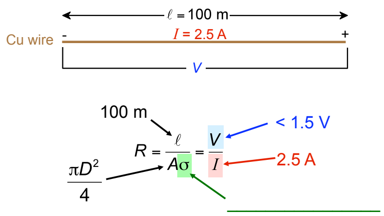
METALS	conductors	____________	
Silver	6.8×10^{7}	Soda-lime glass	10^{-10}-10^{-11}
Copper	6.0×10^{7}	Concrete	10^{-9}
Iron	1.0×10^{7}	Aluminum oxide	$<10^{-13}$
____________		POLYMERS	
Silicon	4×10^{-4}	Polystyrene	$<10^{-14}$
Germanium	2×10^{0}	Polyethylene	10^{-15}-10^{-17}
GaAs	10^{-6}		
	semiconductors		____________

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

Chapter 18 - 6

Example: Conductivity Problem

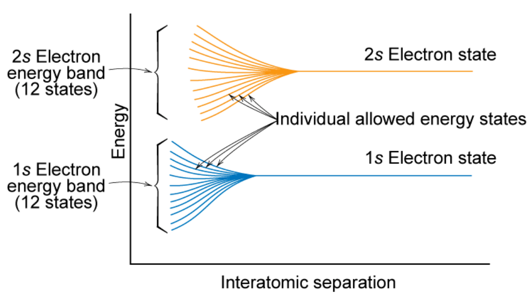
What is the minimum diameter (D) of the wire so that V < 1.5 V?



Solve to get $D >$ ____________

Chapter 18 - 7

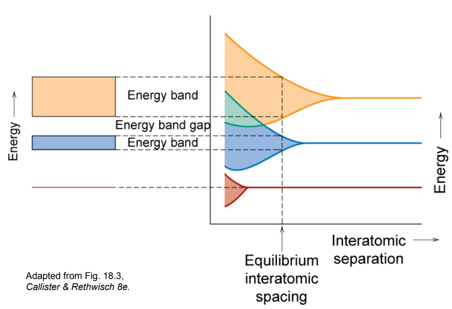
Electron Energy Band Structures



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

Chapter 18 - 8

Band Structure Representation



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

Chapter 18 - 9

Conduction & Electron Transport

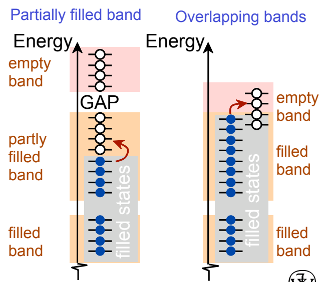
- Metals (____________):

-- for metals _________________ are adjacent to filled states.

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

-- two types of band structures for metals

- ________________
- empty band that overlaps filled band

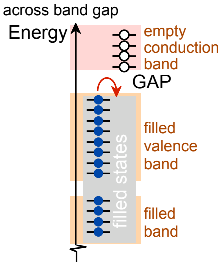


Energy Band Structures: Insulators & Semiconductors

- ______________:

-- wide band gap (_____ eV)

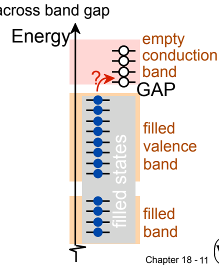
-- few electrons excited across band gap



- _________________:

-- narrow band gap (____ eV)

-- more electrons excited across band gap



Metals: Influence of Temperature and Impurities on Resistivity

- ________________________ increases resistivity

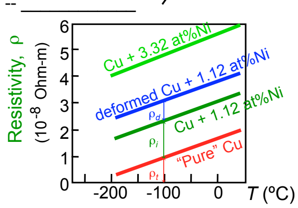
-- grain boundaries

-- ____________

-- impurity atoms

-- ____________

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 __________ with:

-- temperature

-- wt% impurity

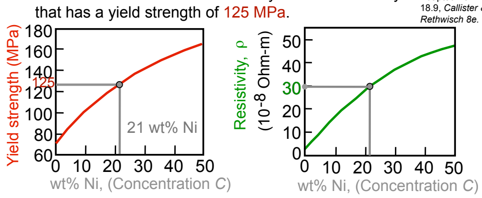
-- %*CW*

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

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:

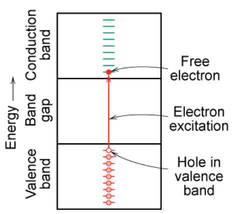
C_{Ni} = ______________ Ni

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

Chapter 18 - 13

Charge Carriers in Insulators and Semiconductors

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



Two ______________________ carriers:

____

- – _________ charge
- – in conduction band

____

- – _________ charge
- – vacant electron state in the valence band

Move at different speeds - drift velocities

Chapter 18 - 14

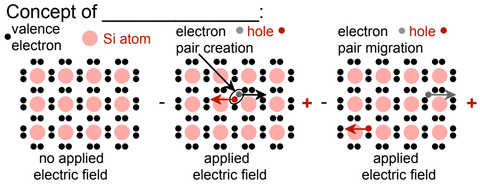
Intrinsic Semiconductors

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

Chapter 18 - 15

Intrinsic Semiconduction in Terms of ______________ Migration

- Concept of ______________:



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

- Electrical ______________ 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)

Chapter 18 - 16

Number of Charge Carriers

__________ Conductivity

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

- for ______ semiconductor $n = p = n_i$

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

- Ex: GaAs

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

For GaAs $\quad n_i =$ ___________

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

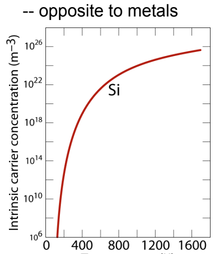
Chapter 18 - 17

Intrinsic Semiconductors: Conductivity vs *T*

- Data for ____________:

  -- σ increases with *T*

  -- opposite to metals



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

____

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

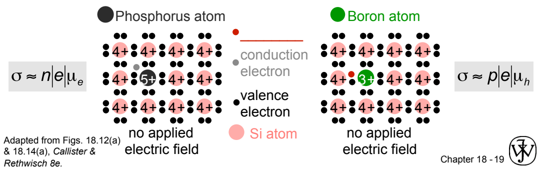
material	band gap (eV)
Si	1.11
Ge	0.67
GaP	2.25
CdS	2.40

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

Chapter 18 - 18

Intrinsic vs Extrinsic Conduction

- __________:
  -- case for pure Si
  -- # electrons = # ________ ($n = p$)
- __________:
  -- electrical behavior is determined by presence of impurities that introduce excess electrons or holes
  -- __________
- *n*-type __________: ($n >> p$) • *p*-type Extrinsic: ($p >> n$)

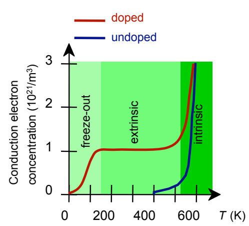


Adapted from Figs. 18.12(a) & 18.14(a), *Callister & Rethwisch 8e.*

Chapter 18 - 19

Extrinsic Semiconductors: Conductivity vs. Temperature

- Data for ______________:
  -- ______________
  -- reason: imperfection sites lower the activation energy to produce mobile electrons.
- Comparison: ________ vs extrinsic conduction...
  -- ____________ 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.)

Chapter 18 - 20

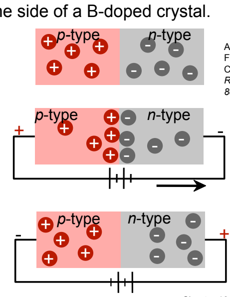
p-n Rectifying Junction

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

-- No applied __________:
__________________.

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

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



Adapted from Fig. 18.21 Callister & Rethwisch 8e.

Chapter 18 - 21

Properties of Rectifying Junction

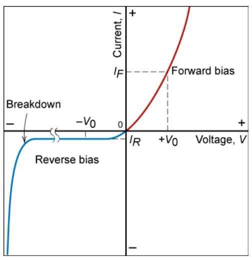


Fig. 18.22, *Callister & Rethwisch 8e.*

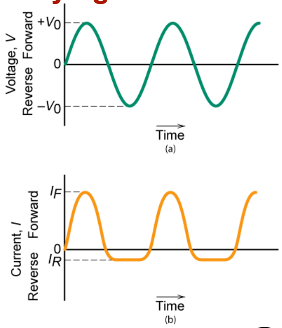


Fig. 18.23, *Callister & Rethwisch 8e.*

Chapter 18 - 22

Junction Transistor

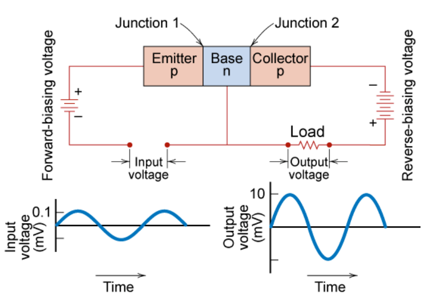


Fig. 18.24, *Callister & Rethwisch 8e.*

Chapter 18 - 23

MOSFET Transistor Integrated Circuit Device

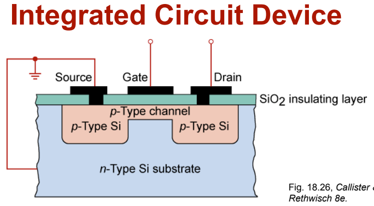


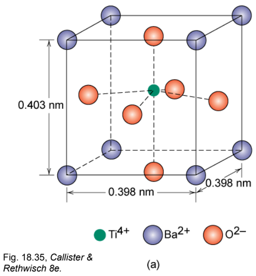
Fig. 18.26, *Callister & Rethwisch 8e.*

- MOSFET (____)
- Integrated circuits - state of the art ca. ___ nm line width
  - ~ 1,000,000,000 components on chip
  - chips formed one layer at a time

Chapter 18 - 24

Ferroelectric Ceramics

- Experience ______________ polarization



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

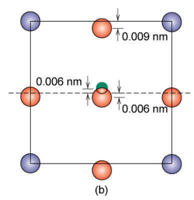


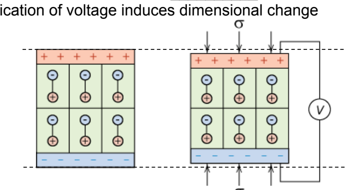
Fig. 18.35, *Callister & Rethwisch 8e.*

Chapter 18 - 25

Piezoelectric Materials

____

– application of stress induces _________
– 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.)

Chapter 18 - 26

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

Chapter 18 - 27