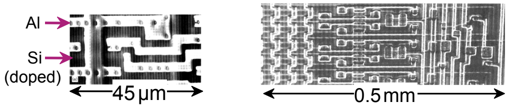
Electrical Properties

ISSUES TO ADDRESS...

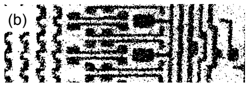
- How are electrical conductance and resistance characterized? (What effects conductance?)
- What are the physical phenomena that distinguish conductors, semiconductors, and insulators?
- For metals, how is conductivity affected by imperfections, temperature, and deformation?
- For semiconductors, how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

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.
  & dark region is Al wiring



Electrical Conduction

- Ohm's Law:

$$V = I\,R$$

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

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

current flow path length
cross-sectional area of current flow

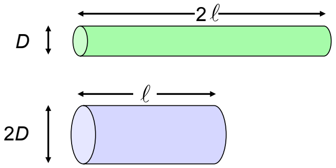
$$\rho = \frac{RA}{\ell}$$

- Conductivity, σ

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

Electrical Properties

- Which will have the greater resistance?



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

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

- Analogous to flow of cars on road
- Resistance depends on sample geometry and size.
- Resistivity of independent of sample geometry

Definitions

Further definitions

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

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

ε = electric field potential $= V/\ell$

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

Electron flux conductivity voltage gradient

Conductivity: Comparison

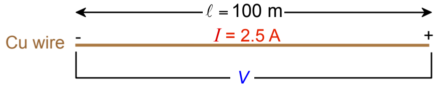
Room temperature values in $(\Omega\text{ - m})^{-1}$

METALS	conductors	CERAMICS	
Silver	6.8 x 10^{7}	Soda-lime glass	10^{-10}-10^{-11}
Copper	6.0 x 10^{7}	Concrete	10^{-9}
Iron	1.0 x 10^{7}	Aluminum oxide	$<10^{-13}$
SEMICONDUCTORS		POLYMERS	
Silicon	4 x 10^{-4}	Polystyrene	$<10^{-14}$
Germanium	2 x 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 9e.*

Example: Conductivity Problem

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



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

100 m

< 1.5 V

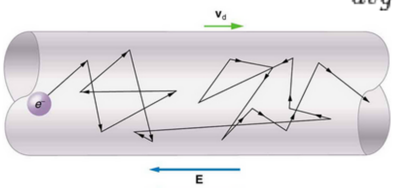
2.5 A

$$\frac{\pi D^2}{4}$$

6.07 x 10^7 (Ohm-m)$^{-1}$

Solve to get $D > 1.87$ mm

Electron Drift $v_{avg} = \mu E$



Electrons are scattered and drift *slowly* in one direction (1.2 in./min in Cu) due to the E field.

However electrical signal "appear" to travels at about 2/3 the speed of light.

As one electron is pushed into "full" pipe, an electron is pushed out the other end.

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

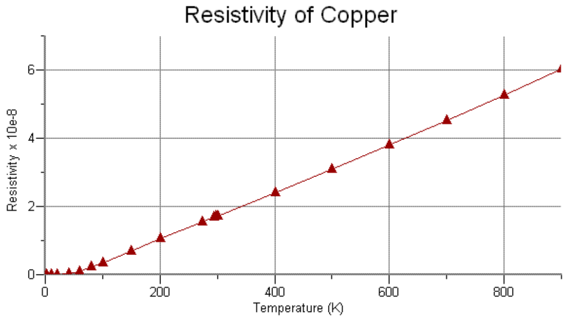
σ – Conductivity
n - # of free electrons/VOL
e - 1.6 X 10^{19} C
μ_e - Electron Mobility

Matthiessen's Rule: The total resistivity of a material is the sum of the contributions from thermal vibrations, impurities, and plastic deformation

$$\rho_{total} = \rho_t + \rho_i + \rho_d$$

t – Thermal Vibrations	-- temperature
i - Impurities	-- wt% impurity
d - Deformation	-- %CW

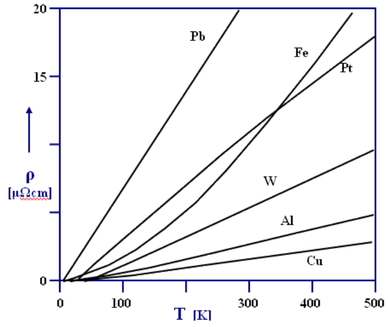
Resistance rises linearly with temperature when T > -200 °C

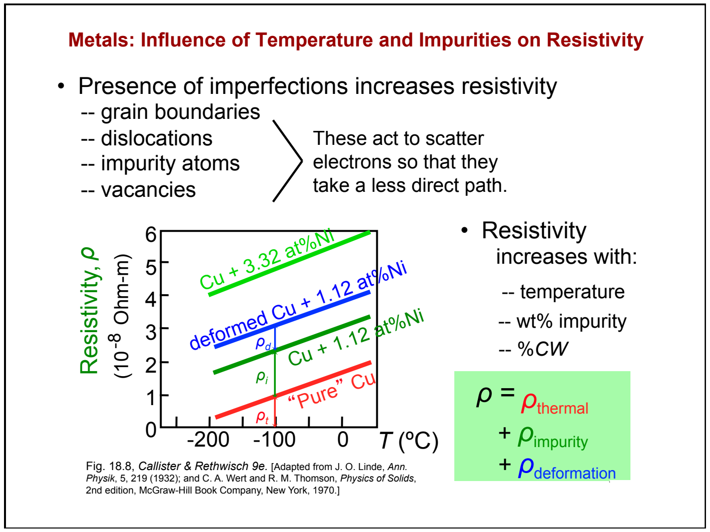


$$\rho_t = \rho_0 + aT$$

Resistance vs. temp for other metals

$$\rho_t = \rho_o + aT$$





Metals: Influence of Temperature and Impurities on Resistivity

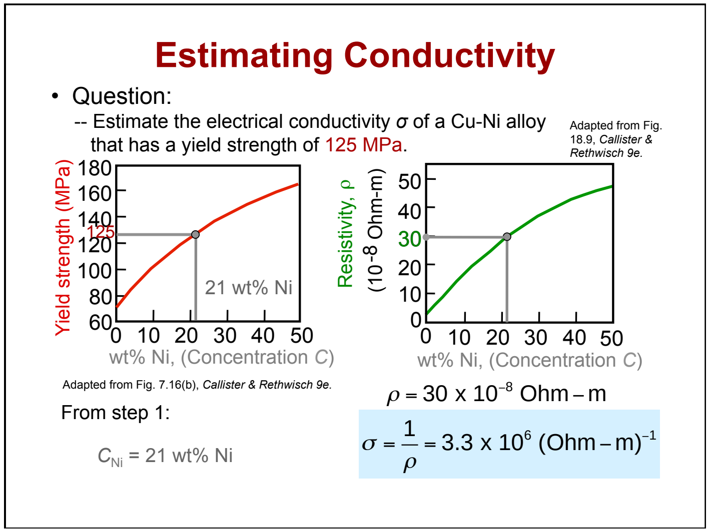
- Presence of imperfections increases resistivity
  - -- grain boundaries
  - -- dislocations
  - -- impurity atoms
  - -- vacancies

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

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

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

Fig. 18.8, *Callister & Rethwisch 9e.* [Adapted from J. O. Linde, *Ann. Physik*, 5, 219 (1932); and C. A. Wert and R. M. Thomson, *Physics of Solids*, 2nd edition, McGraw-Hill Book Company, New York, 1970.]



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 9e.*

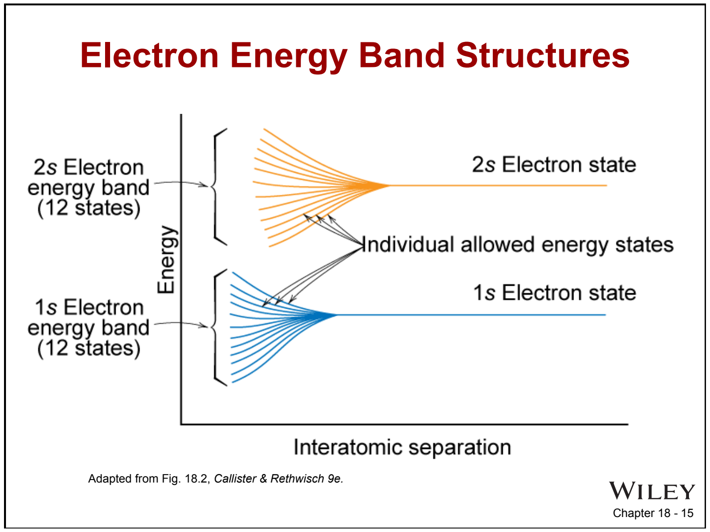
Adapted from Fig. 7.16(b), *Callister & Rethwisch 9e.*

From step 1:

C_{Ni} = 21 wt% Ni

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

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



Electron Energy Band Structures

Adapted from Fig. 18.2, *Callister & Rethwisch 9e.*

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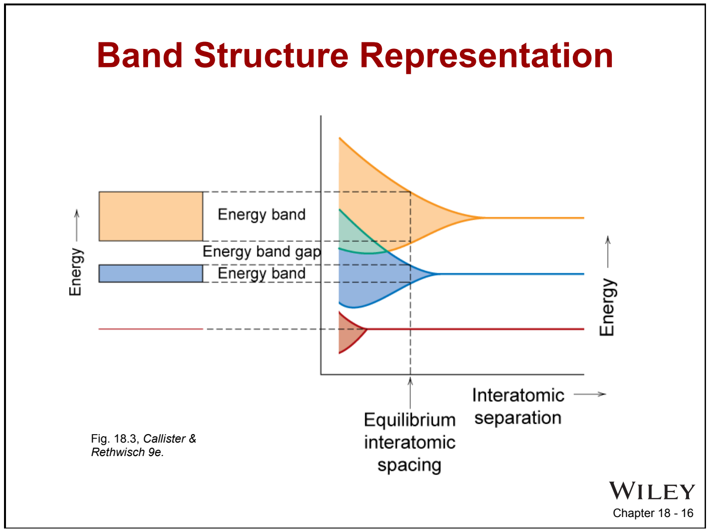

Band Structure Representation

Fig. 18.3, *Callister & Rethwisch 9e.*

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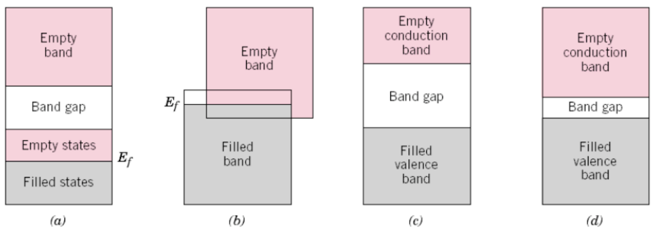
Example band structures at 0K



Metal (Cu) **Metal (Mg)** **Insulator** **Semiconductor**

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Chapter 18 - 17

Conduction & Electron Transport

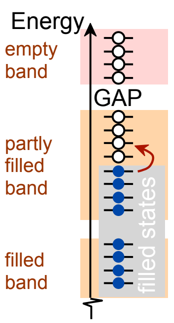
- Metals (Conductors):

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

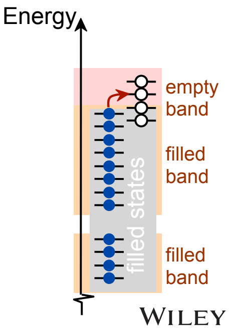
-- thermal energy excites electrons into empty higher energy states.

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

Partially filled band



Overlapping bands



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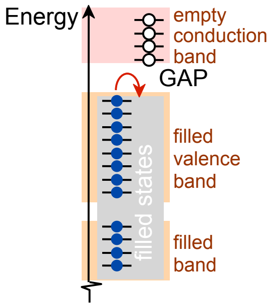
Chapter 18 - 18

Energy Band Structures: Insulators & Semiconductors

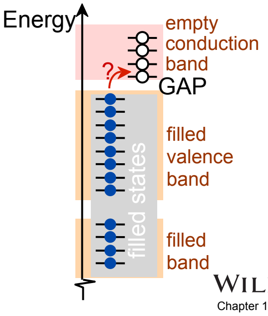
- Insulators:

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



- Semiconductors:

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



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Charge Carriers in Insulators and Semiconductors

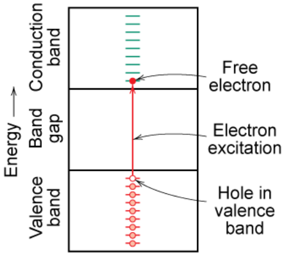

Fig. 18.6 (b), *Callister & Rethwisch 9e.*

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

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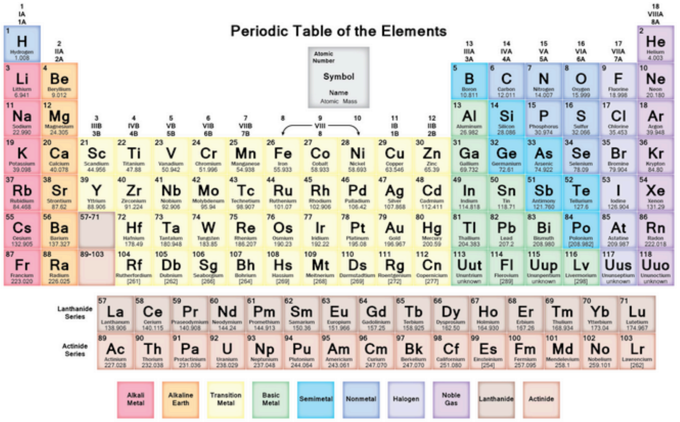
Chapter 18 - 20

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.



Periodic Table of the Elements

Atomic Number
Symbol
Name
Atomic Mass

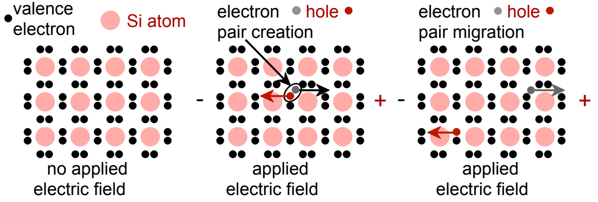
1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	57-71	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	89-103	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo

Lanthanide Series	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinide Series	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Alkali Metal · Alkaline Earth · Transition Metal · Basic Metal · Semimetal · Nonmetal · Halogen · Noble Gas · Lanthanide · Actinide

Intrinsic Semiconduction in Terms of Electron and Hole Migration

- Concept of electrons and holes:



Adapted from Fig. 18.11, *Callister & Rethwisch 9e.*

- 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 $n = p = n_i$

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

- Ex: GaAs

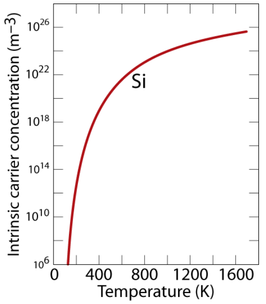
$$n_i = \frac{\sigma}{|e|(\mu_e + \mu_h)} = \frac{10^{-6}(\Omega\cdot\text{m})^{-1}}{(1.6 \text{ x } 10^{-19}\text{C})(0.85 + 0.45 \text{ m}^2/\text{V}\cdot\text{s})}$$

For GaAs $n_i = 4.8 \text{ x } 10^{24} \text{ m}^{-3}$

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

Intrinsic Semiconductors: Conductivity vs *T*

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



Adapted from Fig. 18.16, *Callister & Rethwisch 9e.*

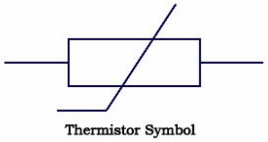
$$\sigma = n_i |e| (\mu_e + \mu_h)$$

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

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

Selected values from Table 18.3, *Callister & Rethwisch 9e.*

Thermistors as temperature sensors – devices made from semiconductor material. Their resistance decreases with increasing temperature.



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Chapter 18 -

Comparing Si to Cu at room temp.

- **μ_{cu} = 30 cm^2/V-S**
- **n_{cu} = 10^{29} /cm^2**
- **μ_{si} = 1400 cm^2/V-S**
- **n_{si} = 10^{16} /cm^2**

Electrons are 50 times more mobile in Si than in Cu but there are many more free electrons in Cu, therefore Cu is 200,000,000,000 times less resistive compared to copper.

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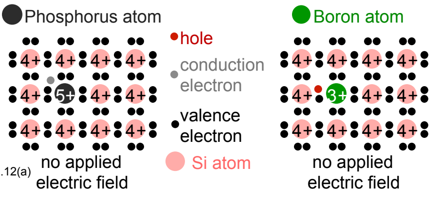
Chapter 18 - 28

Intrinsic vs Extrinsic Conduction

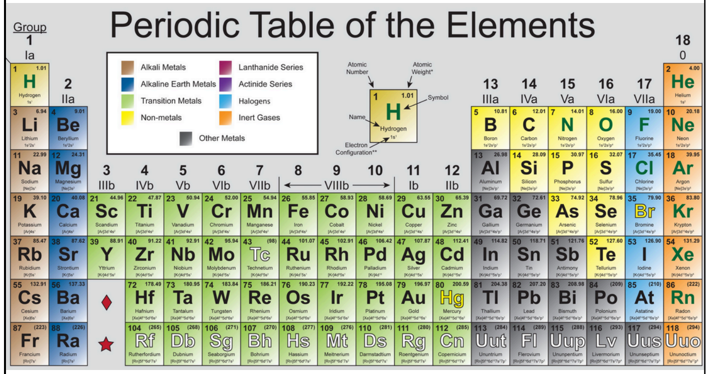
- Intrinsic:
  -- case for pure Si
  -- # electrons = # holes ($n = p$)
- Extrinsic:
  -- electrical behavior is determined by presence of impurities that introduce excess electrons or holes
  -- $n \neq p$
- *n*-type Extrinsic: ($n >> p$)
- *p*-type Extrinsic: ($p >> n$)

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



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

Adapted from Figs. 18.12(a) & 18.14(a), *Callister & Rethwisch 9e.*



Periodic Table of the Elements

Alkali Metals	Lanthanide Series
Alkaline Earth Metals	Actinide Series
Transition Metals	Halogens
Non-metals	Inert Gases
Other Metals	

Atomic Number
Atomic Weight*
Symbol
Name
Electron Configuration**

Group 1 Ia	2 IIa	3 IIIb	4 IVb	5 Vb	6 VIb	7 VIIb	8	9 VIIIb	10	11 Ib	12 IIb	13 IIIa	14 IVa	15 Va	16 VIa	17 VIIa	18 0
1 H 1.01 Hydrogen																	2 He 4.00 Helium
3 Li 6.94 Lithium	4 Be 9.01 Beryllium											5 B 10.81 Boron	6 C 12.01 Carbon	7 N 14.01 Nitrogen	8 O 16.00 Oxygen	9 F 19.00 Fluorine	10 Ne 20.18 Neon
11 Na 22.99 Sodium	12 Mg 24.31 Magnesium											13 Al 26.98 Aluminum	14 Si 28.09 Silicon	15 P 30.97 Phosphorus	16 S 32.07 Sulfur	17 Cl 35.45 Chlorine	18 Ar 39.95 Argon
19 K 39.10 Potassium	20 Ca 40.08 Calcium	21 Sc 44.96 Scandium	22 Ti 47.87 Titanium	23 V 50.94 Vanadium	24 Cr 52.00 Chromium	25 Mn 54.94 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.69 Nickel	29 Cu 63.55 Copper	30 Zn 65.39 Zinc	31 Ga 69.72 Gallium	32 Ge 72.61 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.90 Bromine	36 Kr 83.80 Krypton
37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc (98) Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.91 Rhodium	46 Pd 106.42 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.71 Tin	51 Sb 121.76 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
55 Cs 132.91 Cesium	56 Ba 137.33 Barium	♦	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.84 Tungsten	75 Re 186.21 Rhenium	76 Os 190.23 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.38 Thallium	82 Pb 207.20 Lead	83 Bi 208.98 Bismuth	84 Po (209) Polonium	85 At (210) Astatine	86 Rn (222) Radon
87 Fr (223) Francium	88 Ra (226) Radium	★	104 Rf (265) Rutherfordium	105 Db (268) Dubnium	106 Sg (271) Seaborgium	107 Bh (270) Bohrium	108 Hs (277) Hassium	109 Mt (276) Meitnerium	110 Ds (281) Darmstadtium	111 Rg (280) Roentgenium	112 Cn (285) Copernicium	113 Uut (284) Ununtrium	114 Fl (289) Flerovium	115 Uup (288) Ununpentium	116 Lv (293) Livermorium	117 Uus (294) Ununseptium	118 Uuo (294) Ununoctium

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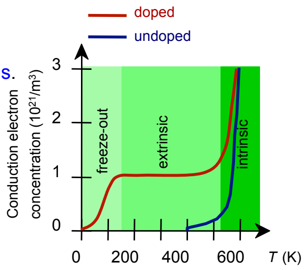
Extrinsic Semiconductors: Conductivity vs. Temperature

Data for Doped Silicon:
σ increases with doping
Reason: dopants donate charge carriers.
Conduction electrons = # of dopant ions.

- 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 $150 \text{ K} < T < 450$ K: "extrinsic"
-- for $T >> 450$ K: "intrinsic"



Adapted from Fig. 18.17, *Callister & Rethwisch 9e.* (From S. M. Sze, *Semiconductor Devices, Physics and Technology.* Copyright © 1985 by Bell Telephone Laboratories, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

Factors That Affect Carrier Mobility

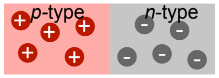
Calculate the room-temperature electrical conductivity of silicon that has been doped with 2 × 10^{23} m–3 of arsenic atoms.

$$\sigma = n|e|\mu_e = (2 \times 10^{23}\ \text{m}^{-3})(1.602 \times 10^{-19}\ \text{C})(0.05\ \text{m}^2/\text{V}-\text{s}) = 1600\ (\Omega-\text{m})^{-1}$$

p-n Rectifying Junction

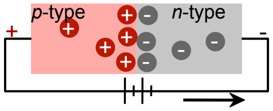
- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current).
- Processing: diffuse P into one side of a B-doped crystal.

-- No applied potential: no net current flow.

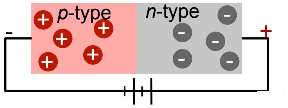


Adapted from Fig. 18.21, *Callister & Rethwisch 9e.*

-- 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

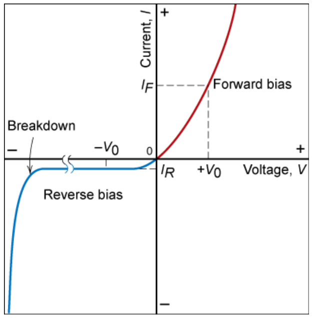


Fig. 18.22, *Callister & Rethwisch 9e.*

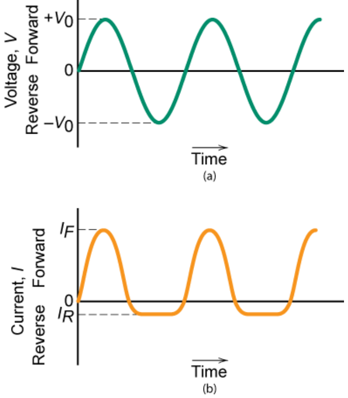
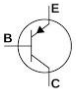


Fig. 18.23, *Callister & Rethwisch 9e.*

Junction Transistor



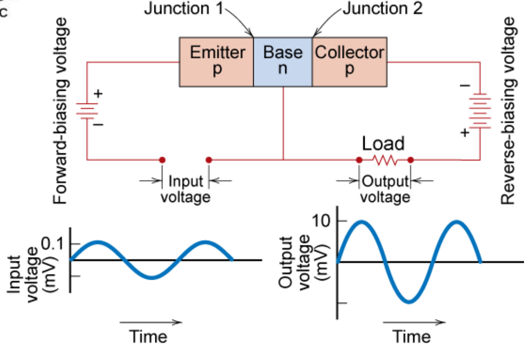
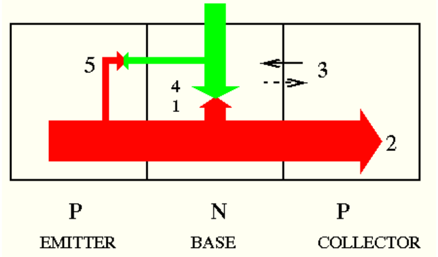


Fig. 18.24, *Callister & Rethwisch 9e.*



MOSFET Transistor Integrated Circuit Device

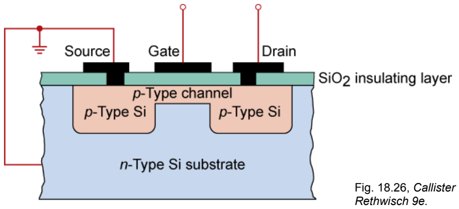
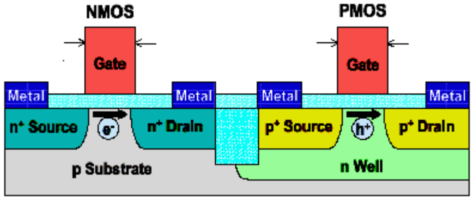


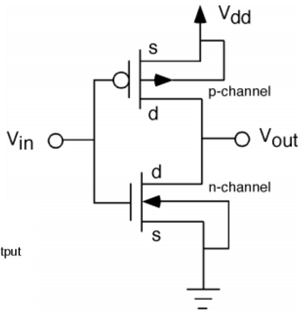
Fig. 18.26, *Callister & Rethwisch 9e.*

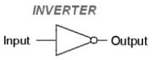
- MOSFET (metal oxide semiconductor field effect transistor)
- Integrated circuits – “state of the art” 50 nm channel width
  - ~ 5,000,000,000 transistors on chip
  - chips formed one layer at a time

CMOS → nMOS + pMOS

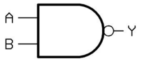


Building simple devices – The Inverter

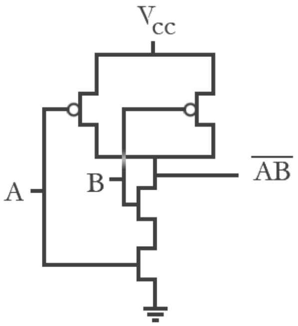




Input	Output
1	0
0	1



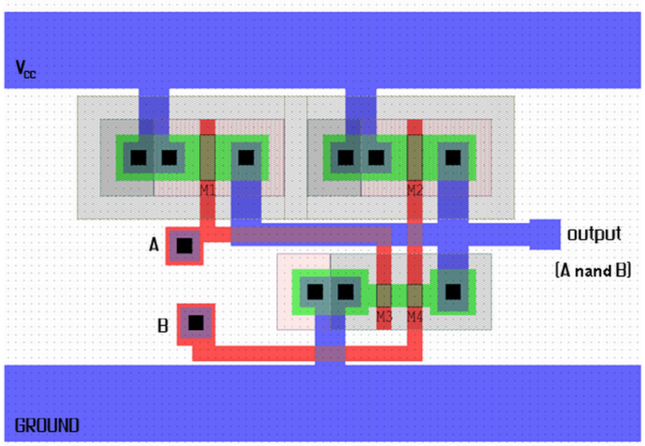
The NAND Gate



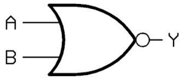
NAND gate

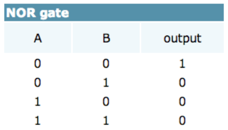
A	B	output
0	0	**1**
0	1	**1**
1	0	**1**
1	1	**0**

NAND gate layout

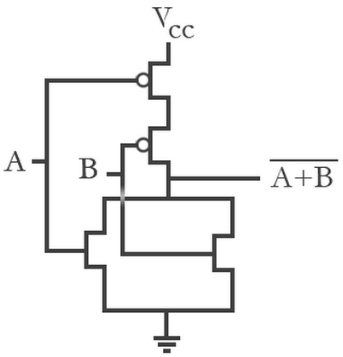


NOR gate



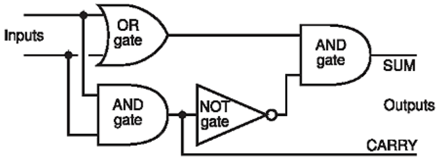


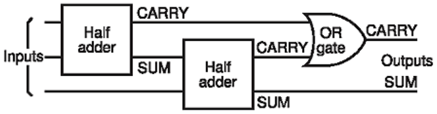
NOR gate		
A	B	output
0	0	1
0	1	0
1	0	0
1	1	0



What can be done with these devices?

Add numbers together!





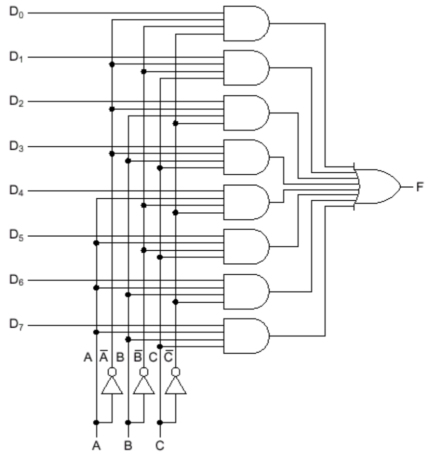


Figure 3-11. An eight-input multiplexer circuit.

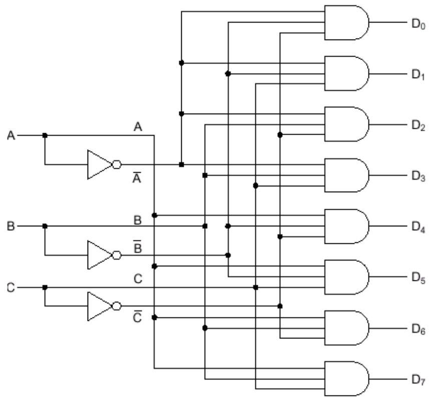


Figure 3-13. A 3-to-8 decoder circuit.

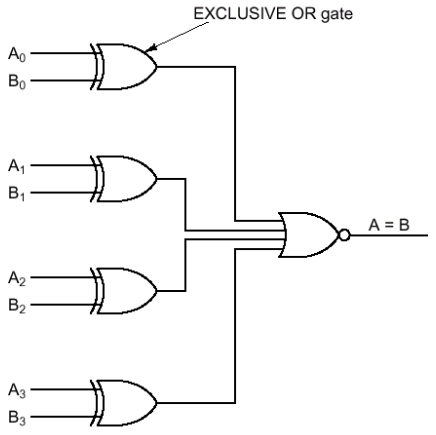
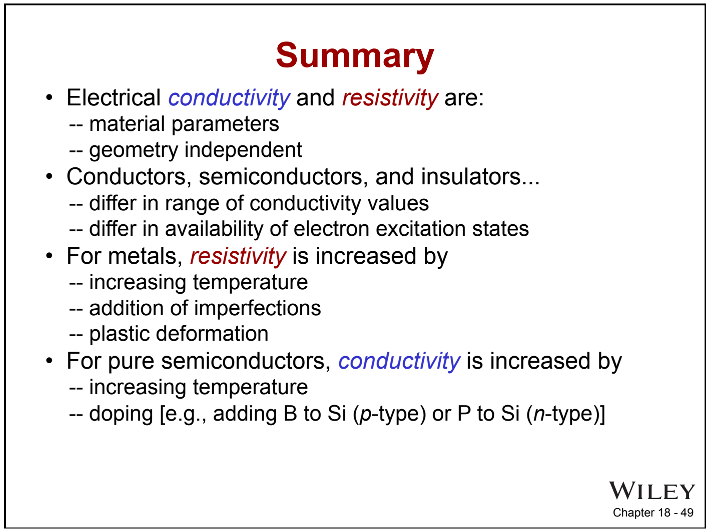


Figure 3-14. A simple 4-bit comparator.

Why can we build devices with semiconductors?

- Semiconductors are neither good insulators or good conductors.
- We can select specific, small regions to be electrically conductive for either holes or electrons.
- Other regions can be made insulating by growing an oxide film
- The electrical properties of the conductive regions can be altered by applying a positive or negative voltage.

- The number of charge carriers in an extrinsic semiconductor (n) is controlled by the number of dopants when temperature is between 150- 450 K.
- Using dopants we can create regions within si that have an engineered value for conductivity.
- Certain regions can be made conductive for certain types of charge carriers by applying a voltage.



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)]

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