Chapter 7: 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, temperature, and deformation?
- For semiconductors, how is conductivity affected by impurities (doping) and temperature?

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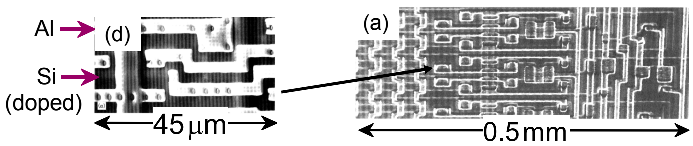
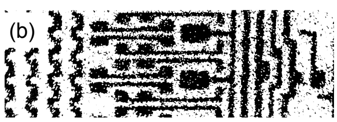
View of an Integrated Circuit

- Scanning electron micrographs of an IC:



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



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

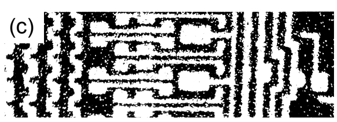


Fig. (d) from Fig. 12.27(a), *Callister & Rethwisch 3e.* (Fig. 12.27 is courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

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

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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

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

surface area of current flow

current flow path length

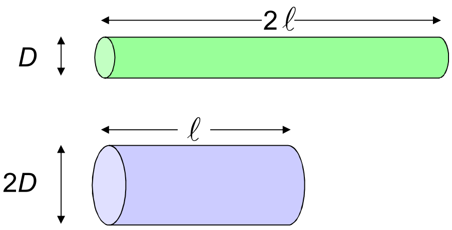
- Conductivity, σ

(Reciprocal of resistivity, ρ)

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

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 water in a pipe
- Resistance depends on sample geometry and size.

Definitions

Further definitions

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

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

$\varepsilon \equiv$ electric field potential $= V / \ell$

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

Electron flux conductivity voltage gradient

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•One way of classifying solid materials is according to the ease with which they conduct an electric current; within this classification scheme there are three groupings:

*1) **Conductors**, 2) **Semiconductors**, and 3) **Insulators**:*

•***"Metals"*** *are* good conductors, typically having conductivities on the order of **10^{7}(Ω-m)$^{-1}$ (Conductors)**

•At the other extreme are materials with very low conductivities, ranging between **10^{-10}** and **10^{-20}(Ω-m)$^{-1}$** these are electrical "**Insulators**".

•Materials with intermediate conductivities, generally from **10^{-6}** to **10^{4}(Ω-m)$^{-1}$** are termed "**Semiconductors**".

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Conductivity: Comparison

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

METALS	conductors	CERAMICS	
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	$<10^{-13}$

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, 18.3, and 18.4, *Callister & Rethwisch 8e.*

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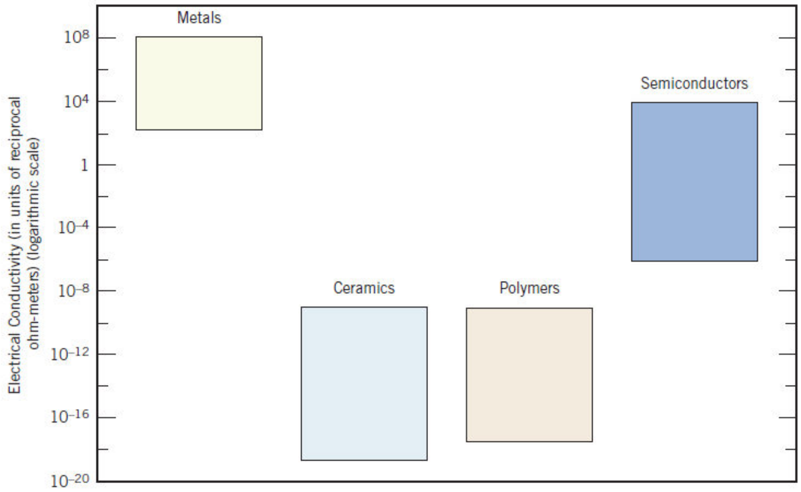
Bar-chart of room temperature **electrical conductivity** ranges for metals, ceramics, polymers and semiconducting materials.



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Ionic Conduction:

•An electric current results from the motion of electrically charged particles in response to forces that act on them from an externally applied electric field.

•Positively charged particles are accelerated in the field direction,
•Negatively charged particles are accelerated in the direction opposite.

•Within most solid materials a current arises from the flow of electrons, which is termed *electronic conduction. In addition, for ionic* materials a net motion of charged ions is possible that produces a current; such is termed **ionic conduction.**

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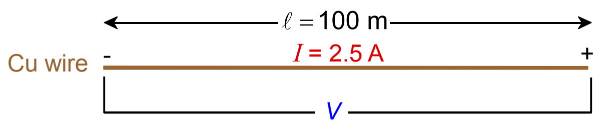
Example: Conductivity Problem

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



100 m

< 1.5 V

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

2.5 A

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

6.07 x 10^7 (Ohm-m)$^{-1}$
(*Known for Cu*)

Solve to get *D* > 1.87 mm

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Electron Energy Band Structures

•In all conductors, semiconductors, and many insulating materials, only electronic conduction exists, and the magnitude of the electrical conductivity is strongly dependent on the number of electrons available to participate in the conduction process:

However, not all electrons in every atom will accelerate in the presence of an electric field.

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Electron Energy Band Structures

The number of electrons available for electrical conduction in a particular material is related to the:

- **Arrangement of electron states or levels with respect to energy**, and then
- **The manner in which these states are occupied by electrons**.

A thorough exploration of these topics is complicated and involves principles of "**quantum mechanics**" that are beyond the scope of this class; **We will omit some concepts and simplify others.**

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Electron Energy Band Structures

Reminder:

•**For each individual atom** there exist discrete energy levels that may be occupied by electrons, arranged into shells and subshells.
•**Shells are designated** by integers (*1*, *2*, *3*, etc.), and subshells by letters (*s*, *p*, *d*, and *f*). For each of *s*, *p*, *d*, and *f* subshells, there exist, respectively, *1*, *3*, *5*, and *7* states.
•**The electrons in most atoms** fill only the states having the lowest energies, two electrons of opposite spin per state (Pauli exclusion principle).
•**The electron configuration** of an isolated atom represents the arrangement of the electrons within the allowed states.

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•A solid may be thought of as consisting of a large number, say, N, of atoms initially separated from one another, which are subsequently brought together and bonded to form the ordered atomic arrangement found in the crystalline material.

• At relatively large separation distances, each atom is independent of all the others and will have the atomic energy levels and electron configuration as if "**isolated**".

•However, as the atoms come within close proximity of one another, electrons are acted upon by the electrons and nuclei of adjacent atoms. This influence is such that each distinct atomic state may split into a series of closely spaced electron states in the solid, to form what is termed an "**electron energy band**".

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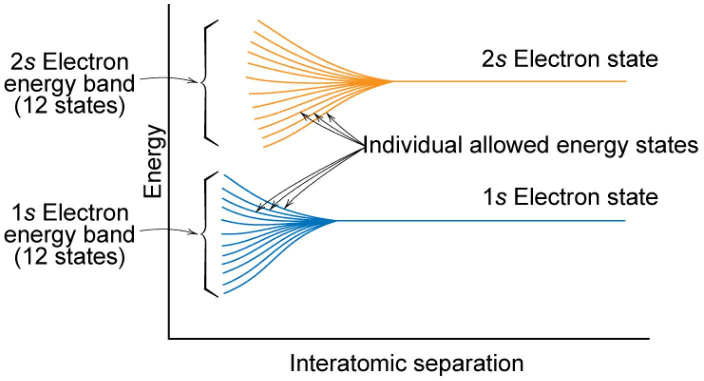
Electron Energy Band Structures

•The extent of splitting depends on interatomic separation and begins with the outermost electron shells (they are the first to be perturbed as the atoms combine together).
•Within each band, the energy states are discrete, yet the **difference between adjacent states is exceedingly small**.



Schematic plot of electron energy versus interatomic separation for an aggregate of 12 Atoms.
Upon close approach, each of the 1*s* and 2*s* atomic states splits to form an electron energy band consisting of 12 states.

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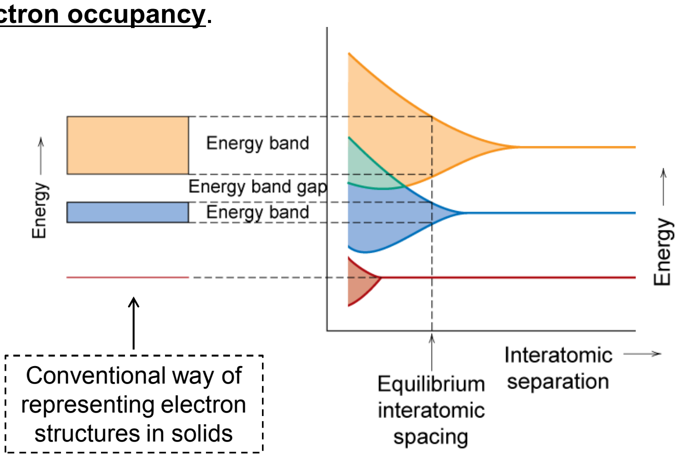
Band Structure Representation

•At the equilibrium spacing, "**band formation**" may **not** occur for the electron subshells nearest the nucleus.
•Furthermore, "**gaps**" may exist between adjacent bands,
•**Energies lying within these** "**band gaps**" **are not available for electron occupancy**.



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•The number of states within each band will equal the total of all states contributed by the *N* atoms. For example, an ***s*** band will consist of N states, and a ***p*** band of 3N states.

•With regard to occupancy, each energy state may accommodate two electrons, which must have oppositely directed spins.

•Furthermore, bands will contain the electrons that resided in the corresponding levels of the isolated atoms; for example, "***4s*** energy band in the solid will contain those isolated atom's ***4s*** electrons". Of course, there will be empty bands and, possibly, bands that are only partially filled.

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The electrical properties of a solid material are a consequence of its electron band structure:

- **The arrangement of the outermost electron bands** and,
- **The way in which they are filled with electrons**.

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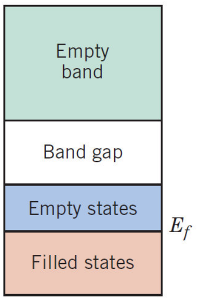
4 different types of band structures are possible at 0 K.

•**In the first**, "**one outermost band is only partially filled**" with electrons. The energy corresponding to the highest filled state at 0 K is called the **Fermi energy.**

This energy band structure is typified by some metals, in particular those that have a single ***s*** valence electron (e.g., copper). Each copper atom has "**one**" *4s* electron; however, for a solid comprised of N atoms, the "4s band" is capable of accommodating 2N electrons. Thus only half the available electron positions within this *4s* band are filled.



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

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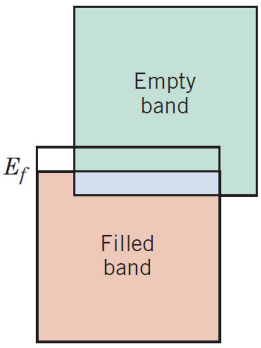
For the second band structure, also found in metals, there is an overlap of an empty band and a filled band.
•Magnesium has this band structure. Each isolated **Mg** atom has "**two**" *3s* electrons. However, when a solid is formed, the *3s* and *3p* bands overlap.



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

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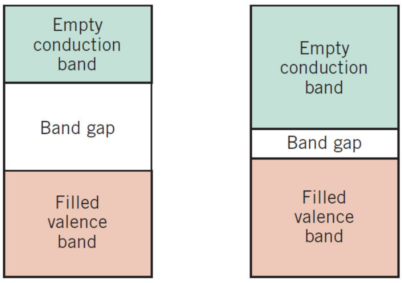
The final two band structures are similar; one band (**the valence band**) that is completely filled with electrons is separated from an empty conduction band, and an energy band gap lies between them.
•For very pure materials, electrons may not have energies within this gap.
•The difference between the two band structures lies in the magnitude of the energy gap;
  •**for** materials that are **insulators**, the band gap is relatively wide,
  •**for semiconductors** it is narrow.

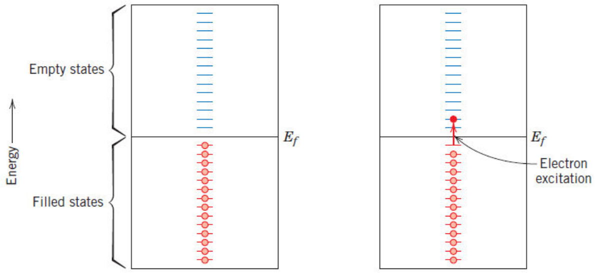


(a) The electron band structure characteristic of insulators; the filled valence band is separated from the empty conduction band by a relatively large band gap (>2eV).
(b) The electron band structure found in the semiconductors, which is the same as for insulators <u>except that the band gap is relatively narrow</u> (<2 eV).

(a- Insulator) (b- Semiconductor)

Metals:

•For an electron to become free, it must be excited or promoted into one of the empty and available energy states above E_f.
•For metals there are vacant energy states adjacent to the highest filled state at E_f. Thus, very little energy is required to promote electrons into the low-lying empty states.
•Generally, the energy provided by an electric field is sufficient to excite large numbers of electrons into these conducting states.



(Before and after an electron excitation)

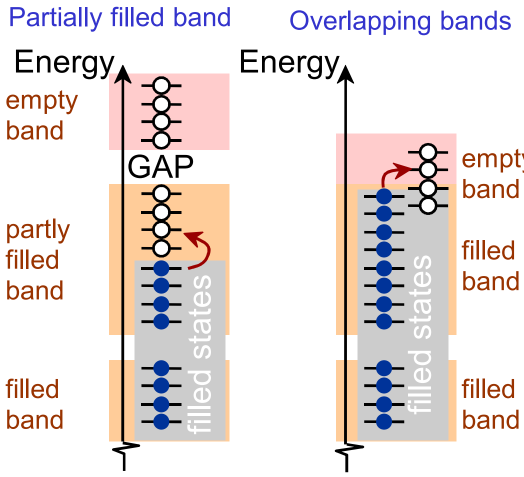
Conduction & Electron Transport

- 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



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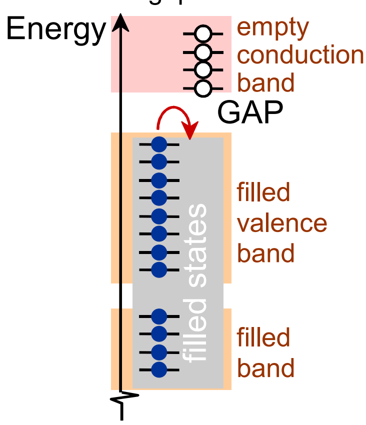
Energy Band Structures: Insulators & Semiconductors

- **Insulators**:

-- wide band gap (> 2 eV)

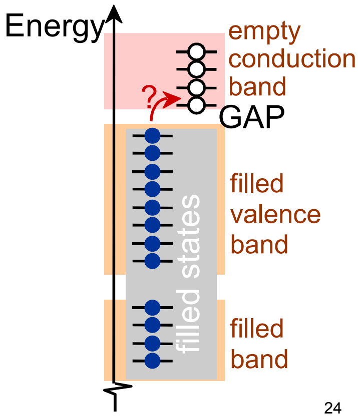
-- few electrons excited across band gap



- **Semiconductors**:

-- narrow band gap (< 2 eV)

-- more electrons excited across band gap



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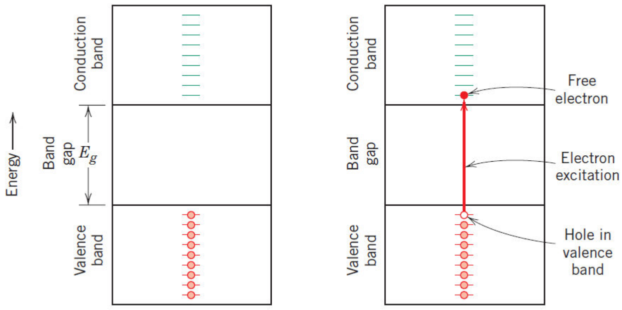
Energy Band Structures: Insulators & Semiconductors

To become free, electrons must be promoted across the energy band gap and into empty states at the bottom of the conduction band. This is possible only by supplying to an electron the difference in energy between these two states, which is approximately equal to the band gap energy, E_g.



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Energy Band Structures: Insulators & Semiconductors

•The number of electrons excited thermally (by heat energy) into the conduction band depends on the "**energy band gap width**" as well as "**temperature**".

•At a given temperature, the larger the E_g the lower is the probability that a valence electron will be promoted into an energy state within the conduction band; this results in fewer conduction electrons.

•In other words, "**the larger the band gap, the lower is the electrical conductivity at a given temperature**".

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Energy Band Structures: Insulators & Semiconductors

•Thus, the distinction between "**semiconductors**" and "**insulators**" lies in the width of the band gap;

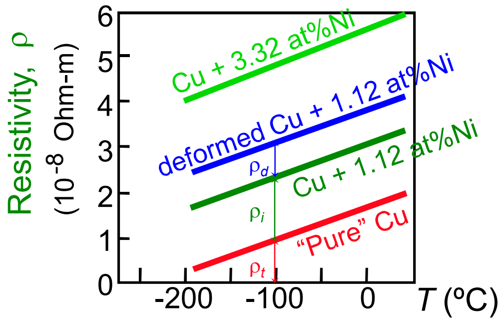
- •for semiconductors it is narrow, whereas
- •for insulating materials it is relatively wide.

•Increasing the temperature of either a "semiconductor" or an "insulator" results in an increase in the thermal energy that is available for electron excitation. Thus, more electrons are promoted into the conduction band, which gives rise to an enhanced conductivity.

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.



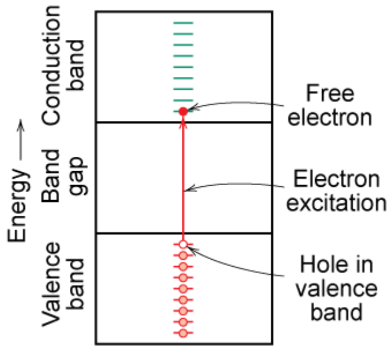
Adapted from Fig. 18.8, *Callister & Rethwisch 8e.* (Fig. 18.8 adapted from J.O. Linde, *Ann. Physik* **5**, p. 219 (1932); and C.A. Wert and R.M. Thomson, *Physics of Solids*, 2nd ed., McGraw-Hill Book Company, New York, 1970.)

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

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

Charge Carriers in Insulators and Semiconductors

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



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

Electron Mobility

•When an electric field is applied, a force is brought to bear on the free electrons; as a consequence, they all experience an acceleration in a direction opposite to that of the field, by virtue of their negative charge.

•According to quantum mechanics, there is no interaction between an accelerating electron and atoms in a perfect crystal lattice.

•Under such circumstances all the free electrons should accelerate as long as the electric field is applied, which would give rise to an electric current that is continuously increasing with time.

Electron Mobility

•However, we know that a current reaches a constant value the instant that a field is applied, indicating that there exist what might be termed "frictional forces".

•These frictional forces result from the scattering of electrons by imperfections in the crystal lattice including:

- -impurity atoms,
- -vacancies,
- -interstitial atoms,
- -dislocations, and
- -thermal vibrations of the atoms themselves.

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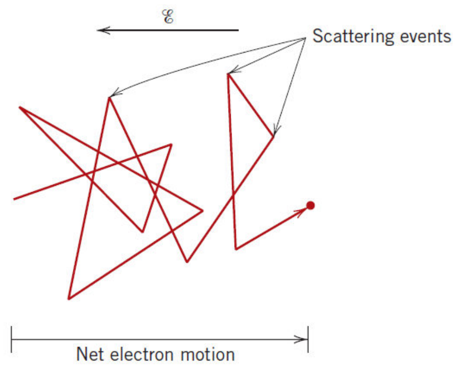
Electron Mobility

•Each scattering event causes an electron to lose kinetic energy and to change its direction of motion. There is, however, some **net electron motion in the direction opposite to the field**, and this flow of charge is the electric current.



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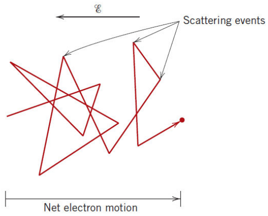
Electron Mobility

The **drift velocity** (v_d):
"the average electron velocity in the direction of the force imposed by the applied field". It is directly proportional to the electric field:



$$v_d = \mu_e \mathscr{E}$$

μ_e : Electron mobility, $m^2/V.s$
ε : Electric field potential

Conductivity:

$$\sigma = n.q.\mu_e$$

n : Number of free or conducting electrons per unit volume
q : Electrical charge ($1.6x10^{-19}$ C)

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SEMICONDUCTORS

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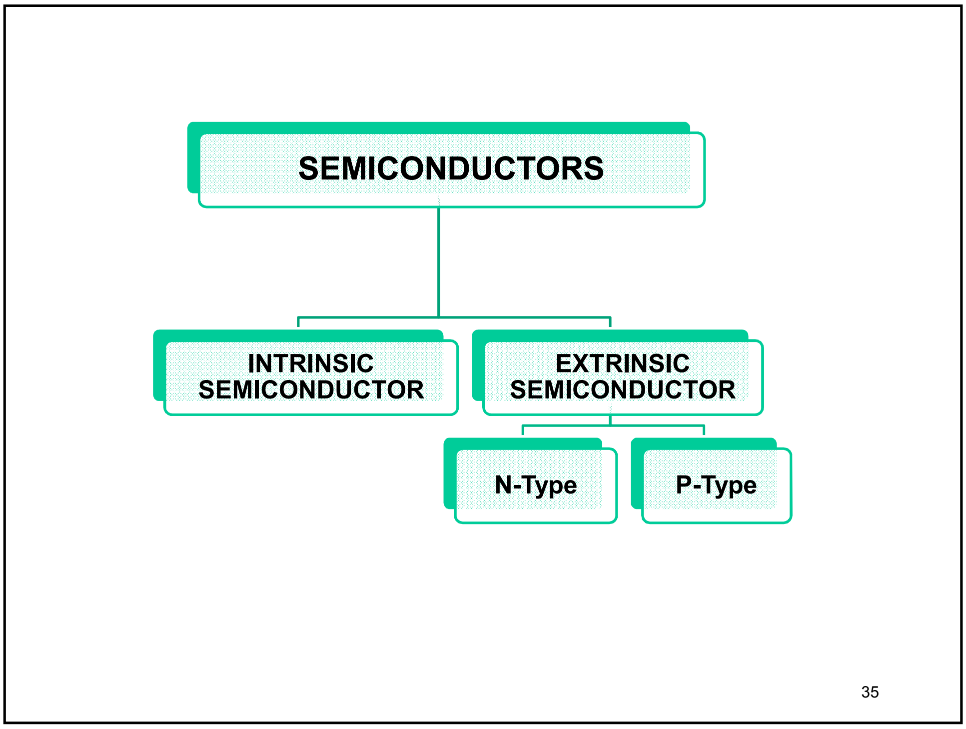
SEMICONDUCTORS
INTRINSIC SEMICONDUCTOR
EXTRINSIC SEMICONDUCTOR
N-Type
P-Type
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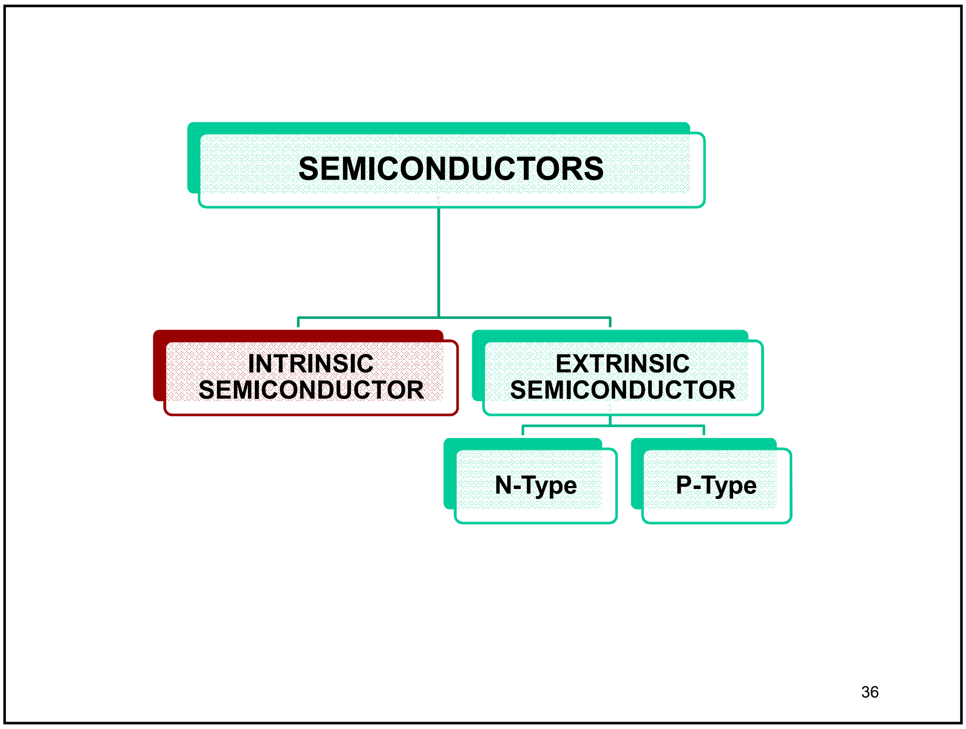
SEMICONDUCTORS
INTRINSIC SEMICONDUCTOR
EXTRINSIC SEMICONDUCTOR
N-Type
P-Type
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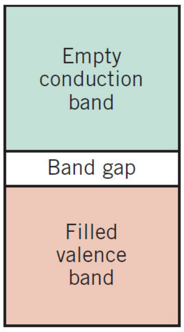
Intrinsic Semiconductors

•**Intrinsic semiconductors** are characterized by the electron band structure, at 0 K, *a completely filled valence band, separated from an empty conduction band by a relatively narrow forbidden band gap*, generally less than 2 eV.

•The two elemental semiconductors are silicon (**Si**) and germanium (**Ge**), having band gap energies of approximately 1.1 and 0.7 eV, respectively.
•Both are found in Group **IVA** of the periodic table and are covalently bonded.



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Intrinsic Semiconductors

•In addition, a host of compound semiconducting materials also display intrinsic behavior.

•One such group is formed between elements of **Groups IIIA and VA**, for example, gallium arsenide (**GaAs**) and indium antimonide (**InSb**); these are frequently called **III–V** compounds.

•The compounds composed of elements of Groups **IIB and VIA** also display semiconducting behavior; these include cadmium sulfide (**CdS**) and zinc telluride (**ZnTe**).

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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

(***As the two elements forming these compounds become more widely separated with respect to their relative positions in the periodic table*** *(i.e., the electronegativities become more dissimilar),* ***the atomic bonding becomes more ionic and the magnitude of the band gap energy increases—the materials tend to become more insulative.***)

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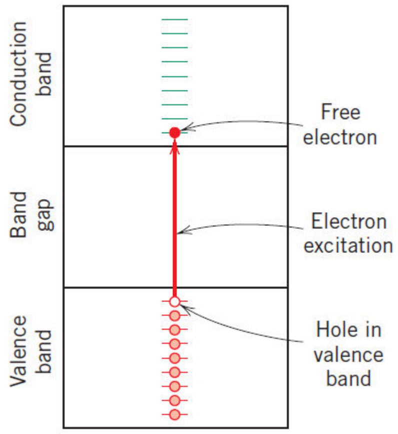
Intrinsic Semiconduction in Terms of Electron and Hole Migration



•In intrinsic semiconductors, for every electron excited into the conduction band there is left behind a missing electron in one of the covalent bonds.
(In the band scheme, a vacant electron state in the valence band.)

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Intrinsic Semiconduction in Terms of Electron and Hole Migration

•Under the influence of an electric field, the position of this missing electron within the crystalline lattice may be thought of as moving by the motion of other valence electrons that repeatedly fill in the incomplete bond.

•This process is expedited by treating a missing electron from the valence band as a positively charged particle called a “**hole**”.

•A hole is considered to have a charge that is of the same magnitude as that for an electron, but of opposite sign ($+1.6\times10^{-19}$ Coulomb).

•Thus, in the presence of an electric field, excited “**electrons**” and “**holes**” move in opposite directions. Furthermore, in semiconductors both electrons and holes are scattered by lattice imperfections.

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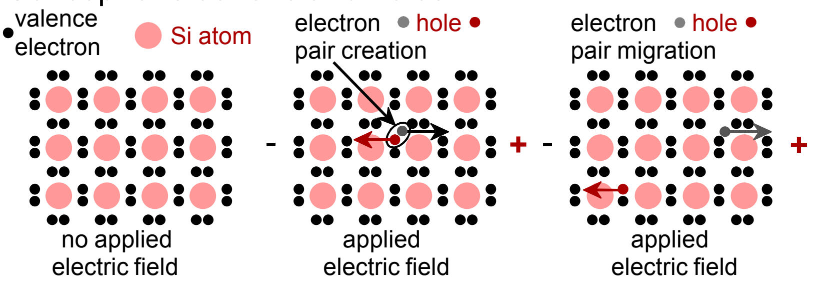
Intrinsic Semiconduction in Terms of Electron and Hole Migration

- Concept of electrons and holes:



- Electrical Conductivity given by:

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

holes/m^3

hole mobility

electrons/m^3

electron mobility

Electrical charge (*1.6×10^{-19} Coulomb*)

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Number of Charge Carriers

Intrinsic Conductivity

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

- for intrinsic semiconductor $n = p = n_i$

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

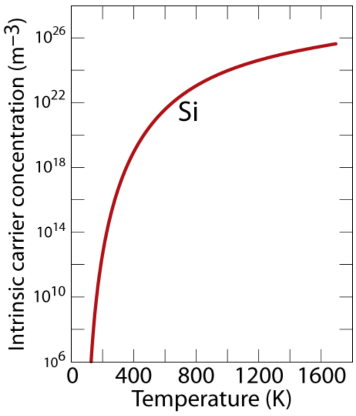
- Ex: GaAs (Gallium Arsenide)

$$n_i = \frac{\sigma}{|e|(\mu_e + \mu_h)} = \frac{10^{-6}(\Omega \cdot \text{m})^{-1}}{(1.6\text{x}10^{-19}\,\text{C})(0.85 + 0.04\,\text{m}^2/\text{V}\cdot\text{s})}$$

For GaAs $\quad n_i = 7.0 \times 10^{12}\ \text{m}^{-3}$

Intrinsic Semiconductors: Conductivity vs T

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



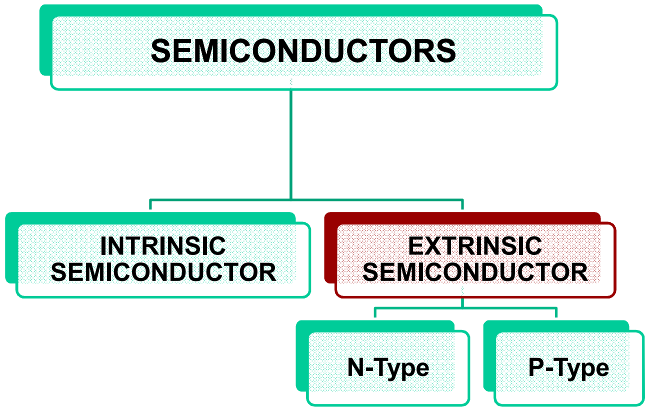
Adapted from Fig. 18.16, *Callister & Rethwisch 8e.*

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

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

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

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



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EXTRINSIC Semiconductors:

•Virtually all commercial semiconductors are extrinsic; that is, <u>the electrical behavior is determined by impurities</u>, which, when present in even minute concentrations, introduce excess electrons or holes.

•**n-Type** Extrinsic Semiconduction.
•**p-Type** Extrinsic Semiconduction.

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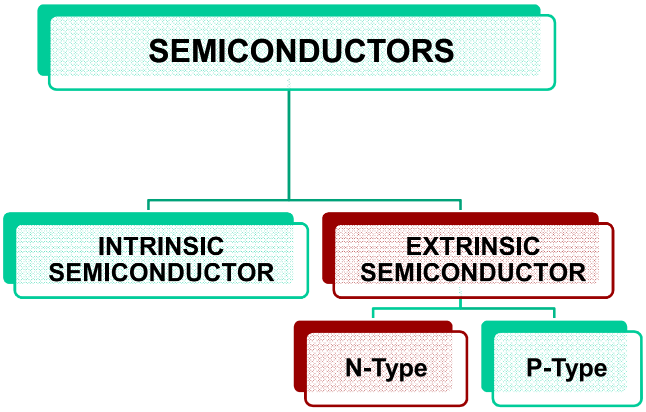

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n-Type Extrinsic Semiconduction:

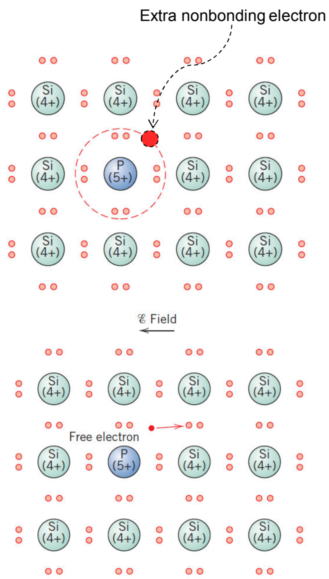
•A **Si** atom has four electrons, each of which is covalently bonded with one of four adjacent Si atoms.

•Suppose that an impurity atom with **a valence of 5** electrons is added as a "**substitutional**" impurity.

•Only "**four**" of "**five**" valence electrons of these impurity atoms can participate in the bonding because there are only four possible bonds with neighboring atoms.

•The extra **nonbonding electron** is loosely bound to the region around the impurity atom by a weak electrostatic attraction.

•*The binding energy* of this electron is relatively small (on the order of 0.01 eV); thus, it is easily removed from the impurity atom, in which case it becomes a free or conducting electron.



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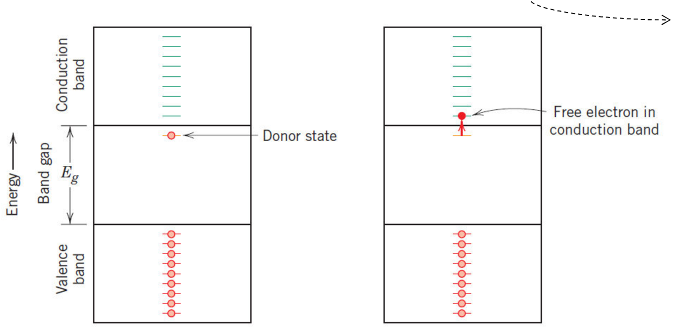
•For each of the loosely bound electrons, there exists a single energy level, or energy state, which is located within the forbidden band gap just below the bottom of the conduction band.

•The electron binding energy corresponds to the energy required to excite the electron from one of these impurity states to a state within the conduction band. Each excitation event "**supplies**" or "**donates**" a single electron to the conduction band; an impurity of this type is termed as **donor**.

•Since each **donor** electron is excited from an impurity level, no corresponding hole is created within the valence band.

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



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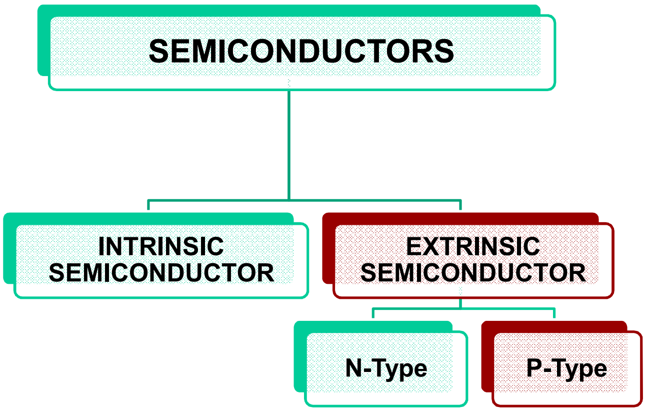

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p-Type Extrinsic Semiconduction:

•An opposite effect is produced by the addition to "**silicon**" or "**germanium**" of trivalent substitutional impurities such as "**aluminum**", "**boron**", and "**gallium**" from Group IIIA.

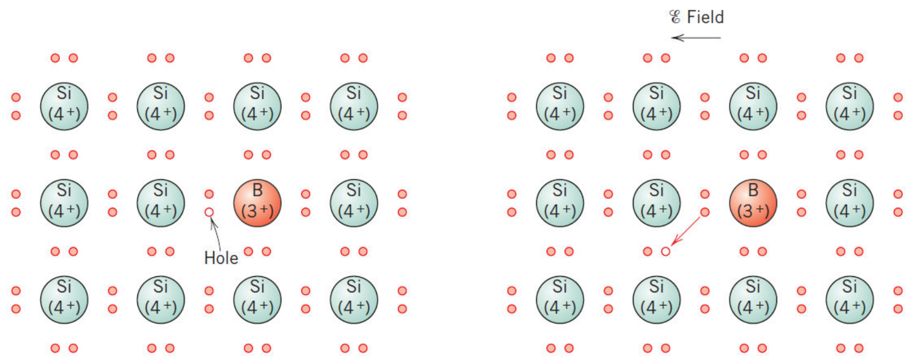
•One of the covalent bonds around each of these atoms is now deficient in an electron; such a deficiency may be viewed as a "**hole**" that is weakly bound to the impurity atom.

•This hole may be liberated from the impurity atom by the transfer of an electron from an adjacent bond.

•Essentially, **the electron and the hole exchange positions**.

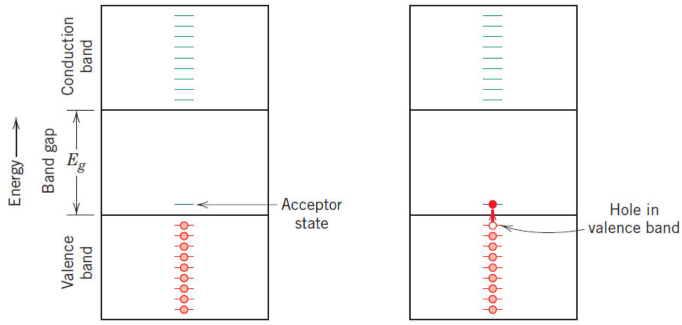
p-Type Extrinsic Semiconduction:

•A moving hole is considered to be in an excited state and participates in the conduction process, in a manner similar to an excited donor electron.



p-Type Extrinsic Semiconduction:

•Each impurity atom of this type introduces an energy level within the band gap, above yet very close to the top of the valence band.
•A hole is imagined to be created in the valence band by the thermal excitation of an electron from the valence band into this impurity electron state.



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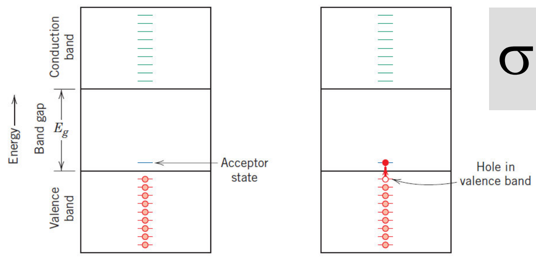
p-Type Extrinsic Semiconduction:

•With such a transition, only one carrier is produced: **a hole in the valence band**; a free electron is not created in either the impurity level or the conduction band.
•An impurity of this type is called an "**acceptor**", because it is capable of accepting an electron from the valence band, leaving behind a hole. It follows that the energy level within the band gap introduced by this type of impurity is called an **acceptor state.**



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

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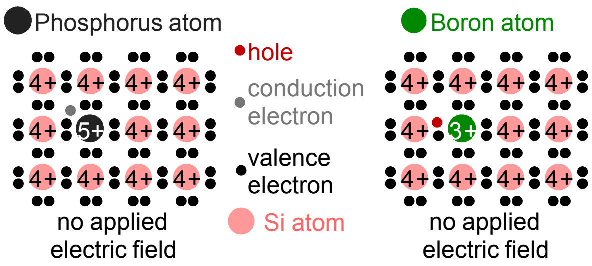
Intrinsic vs Extrinsic Conduction

- 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: ($p >> n$)

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



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

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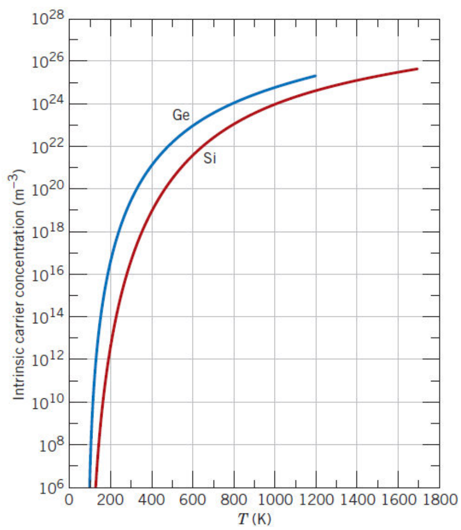
Intrinsic Semiconductors: Conductivity vs. Temperature



- The concentrations of electrons and holes increase with temperature (*more thermal energy is available to excite electrons from the valence to the conduction band*).
- Carrier concentration in **Ge** is greater than for **Si** (*germanium has smaller band gap*).

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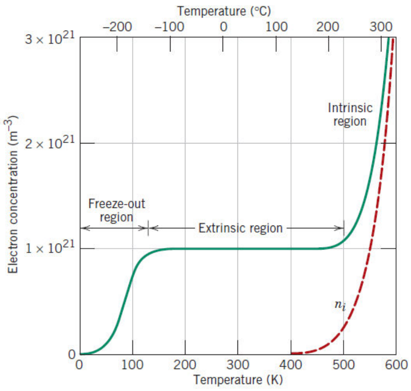
Extrinsic Semiconductors: Conductivity vs. Temperature

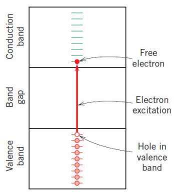


Electron concentration versus temperature for Si (n-type) that has been doped with **10^{21}** m^{-3} of a donor impurity (P), and for intrinsic Si

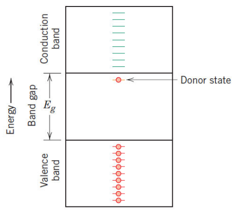
- **At Lower Temperatures**: The thermal energy is insufficient to excite electrons from the P donor level into the conduction band.
- **At Intermediate Temperatures**: Electrons in the conduction band are excited from the P donor state, *and* since the electron concentration is approximately equal to the P content (10^{21} m^{-3}) virtually all of the phosphorus atoms have been ionized.
- **At High Temperatures**: The semiconductor becomes intrinsic; that is, charge carrier concentrations resulting from electron excitations across the band gap first become equal to and then completely overwhelm the donor carrier contribution with rising temperature.

Relations between the electrical conductivity and Temperature:

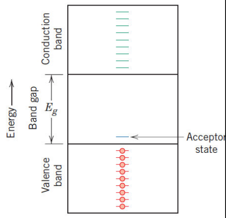
$$\sigma = \sigma_0 e^{-E_g/2kT}$$



$$\sigma = \sigma_0 e^{-(E_g - E_d)/kT}$$



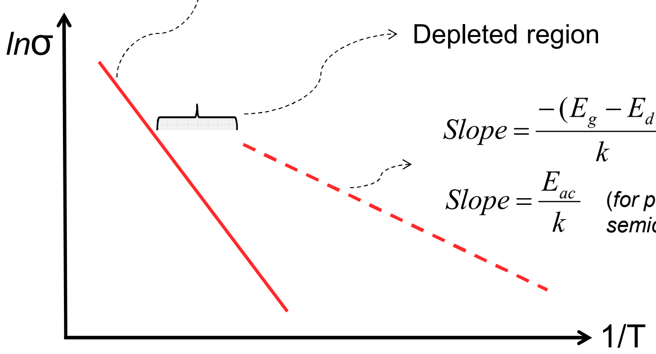
$$\sigma = \sigma_0 e^{-E_{ac}/kT}$$



Relations between the electrical conductivity and Temperature:

$$\sigma = \sigma_0 e^{-E_g/2kT} \Longrightarrow \ln\sigma = \ln\sigma_0 - \frac{E_g}{2k}\frac{1}{T}$$

$$Slope = \frac{E_g}{2k}$$ (*for intrinsic semiconductors*)



$$Slope = \frac{-(E_g - E_d)}{k}$$ (*for n-type extrinsic semiconductors*)

$$Slope = \frac{E_{ac}}{k}$$ (*for p-type extrinsic semiconductors*)

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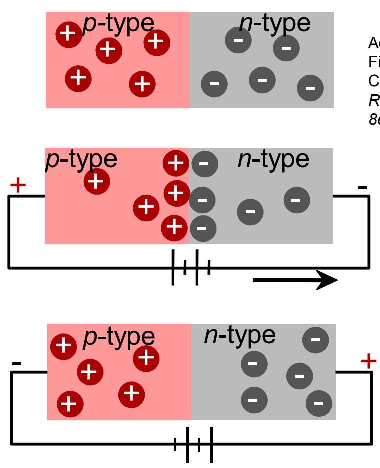
p-n Rectifying Junction

- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current).

-- **No applied potential**: no net current flow.

-- **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**.



Adapted from Fig. 18.21 Callister & *Rethwisch 8e.*

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Properties of Rectifying Junction

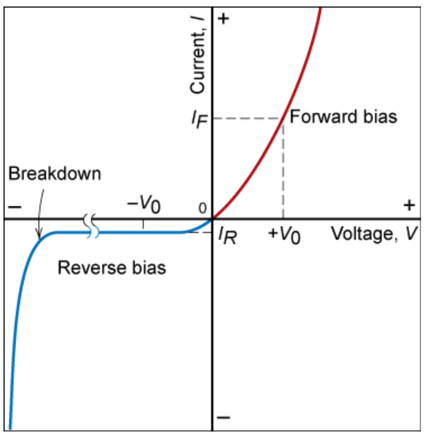

Fig. 18.22, *Callister & Rethwisch 8e.*

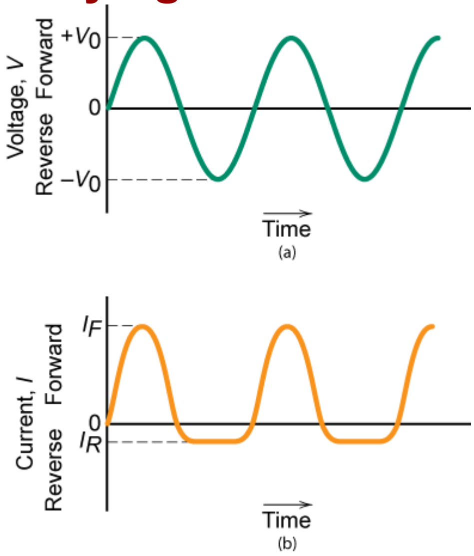

Fig. 18.23, *Callister & Rethwisch 8e.*

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Junction Transistor

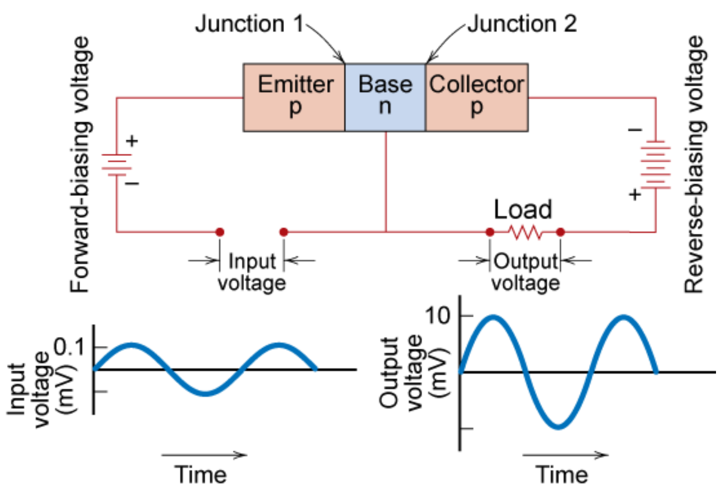

Fig. 18.24, *Callister & Rethwisch 8e.*

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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