Electrical properties of materials

Response of a material to an applied electric field.

phenomenon of electrical conduction:
- Its mathematical expression,
- mechanism of conduction by electrons,
- how the electron energy band structure of a material influences its ability to conduct.

Electrical Conduction

OHM'S LAW

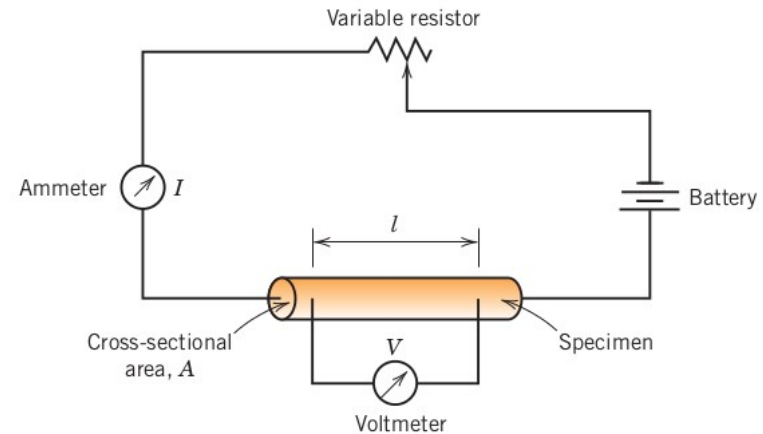Ohm's law relates the current I—or time rate of charge passage—to the applied voltage V

$$V = IR$$

where R is the resistance of the material through which the current is passing.

Units: V: volts (J/C)
     I: amperes (C/s), and
    R: ohms (V/A)

Resistance as a material property

- Independent of current.
- Depends on sample dimensions

The quantity independent of sample dimension is called **electrical resistivity**

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

A: cross-sectional area perpendicular to the direction of the current
l: distance between the two points at which the voltage is measured

It is a material property that depends on material composition, structure, or temperature.

Units of ρ?

Another paramater for understanding electrical character of materials

Electrical conductivity, σ: ease with which a material is capable of conducting an electric current

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

Units of σ?

Alternate expression for electrical resistance

$$J = \sigma \mathcal{E} \qquad \text{----------- (1)}$$

J: current density—the current per unit of specimen area, **J = I/A**,
$\mathcal{E}$: electric field intensity, or the voltage difference between two points divided by the distance separating them, $\boldsymbol{\mathcal{E} = V/l}$

Let us derive the expression of resistance from equation (1)?
Is it the same as V = IR?

Que: (a) Compute the electrical conductivity of cylindrical silicon specimen 4.7 mm in diameter and 47 mm in length in which a current of 0.1 A passes in an axial direction. A voltage of 12.5 V is measured across two probes that are separated by 41 mm.

(b) Compute the resistance over the entire 47 mm of the specimen.

Interesting fact!

Solid materials exhibit an amazing range of electrical conductivities, extending over 27 orders of magnitude

Solids are typically classified according to the ease with which they conduct an electric current

- conductors,
- semiconductors, and
- insulators

What is the range of electrical conductivity in these materials?
Find out a few materials belonging to each class.

Energy band structure in solids

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

How do the participating electrons acelerate in the presence of electric field?

This depends on
- arrangement of electron states or levels (orbitals) with increasing energy, and
- manner in which these states are occupied by electrons
- The resulting electronic configuration of materials.

How many electronic states are present in *s, p* and *d* orbitals?
Write down the electronic configuration of Fe, Cu, Zn and Au.
Describe Pauli's exclusion principle and Hund's rule.

The electrons in most atoms fill only the
states having the lowest energies—two electrons of opposite spin per state, in accord-
ance with the Pauli exclusion principle.

The electron configuration of an isolated atom
represents the arrangement of the electrons within the allowed states.

What happens to electronic states when a solid material forms?

A solid material has a very large number of atom, say 10^{23} atoms, initially separated,
from one another.

At large separation, atoms behave independently, so their electronic configuration is intact.

What happens when the atoms are brough together and bonded to form the
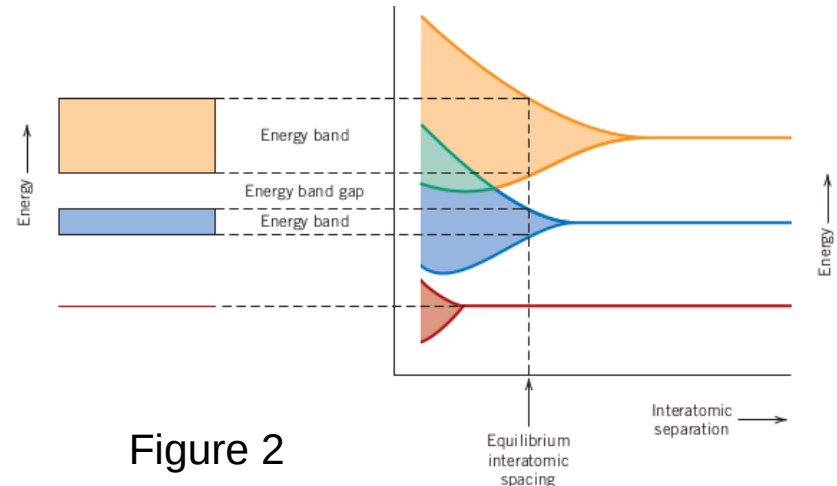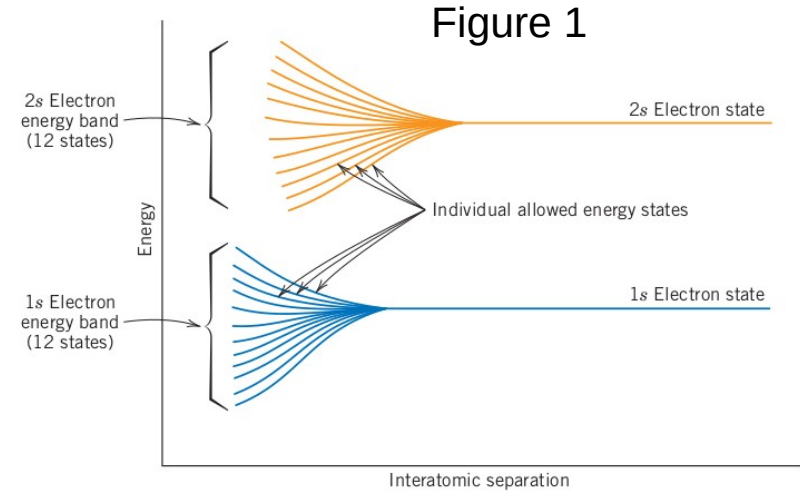ordered atomic arrangement in the crystalline material?

As the atoms come within close proximity of one another,
- electrons are acted upon, or perturbed, by the electrons and nuclei of adjacent atoms.
- this influence of neighbouring nuclei is such that each distinct atomic state (for example, 2s state) may split into a series of closely spaced electron states in the solid to form an **electron energy band**.
- the valence band of an atom undergoes splitting.
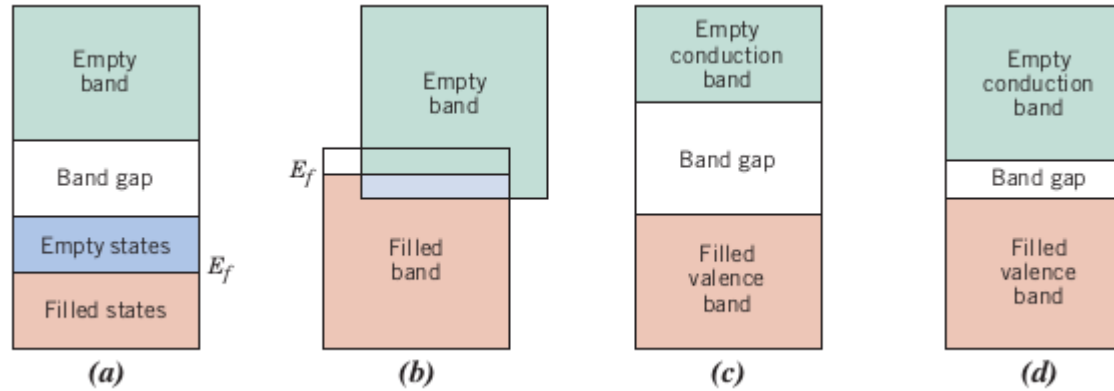- extent of splitting depends on interatomic separation.
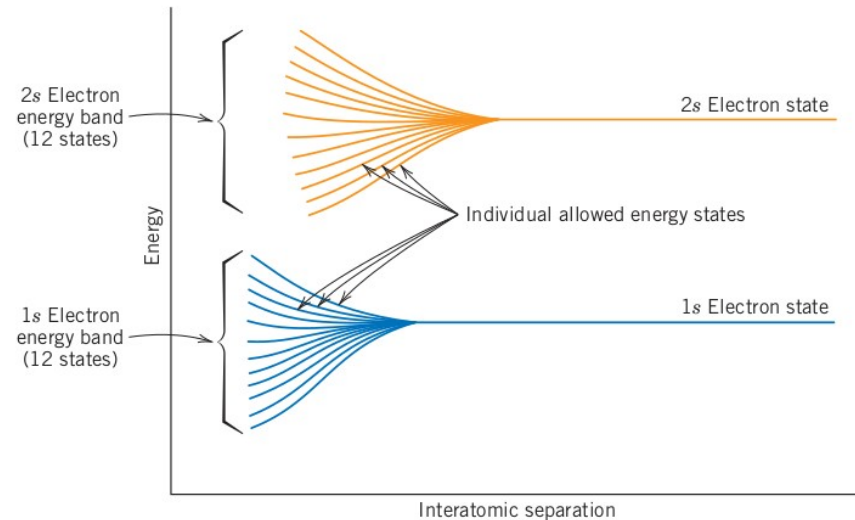
Let us understand the features of electron bands...

- Within each band, the energy states are discrete, yet the difference between adjacent states is exceedingly small.
- gaps may exist between adjacent bands, as in Figure 1.
- energies lying within these band gaps are not available for electron occupancy.
- the number of states within each band is equal to the total of all states contributed by the N atoms (for example, an *s* band consists of N states and a *p* band of 3N states).
- each energy state may accommodate two electrons that must have oppositely directed spins.
- In case of empty states, bands are only partially filled.

Figure 1

2s Electron energy band (12 states)

2s Electron state

Energy

Individual allowed energy states

1s Electron energy band (12 states)

1s Electron state

Interatomic separation

Figure 2

Energy

Energy band

Energy band gap

Energy band

Energy

Interatomic separation

Equilibrium interatomic spacing

Four types of band structures

Can we understand these in terms of nature of filling (partial or complete), and band gap?

Four types of band structures

(a) (b) (c) (d)
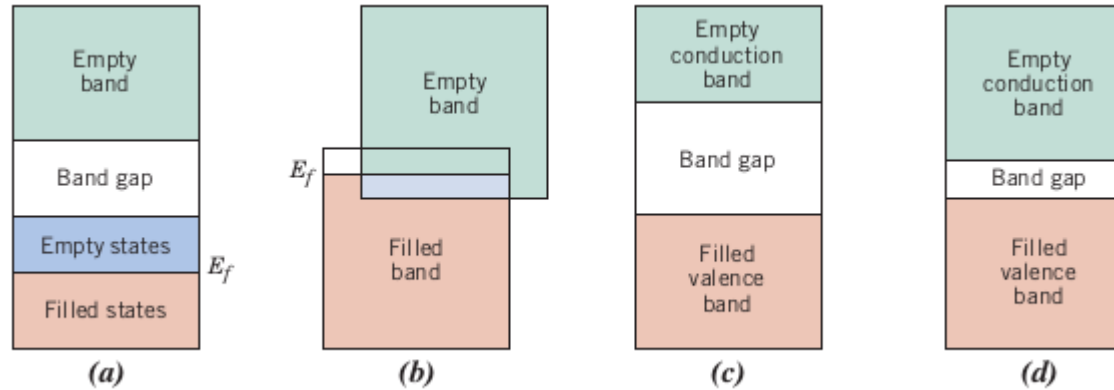
In (a), one outermost band is only partially filled with electrons.
The energy corresponding to the highest filled state at 0 K is called the Fermi energy E_f.
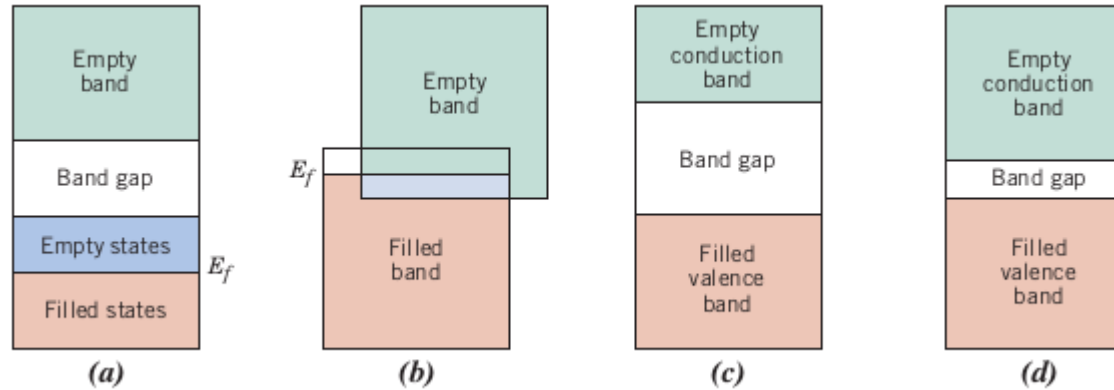Copper metal shows this type of band structure.

In (b), there is an overlap of an empty band and a filled band.
Most metals show this type of band structure.
Eg. Magnesium.
Here, the Fermi energy is taken as that energy below which, for N atoms, N states are filled, two electrons per state.

Four types of band structures

(a) (b) (c) (d)

In (c) and (d), 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.

For materials that are <u>insulators</u>, the band gap is relatively wide (c),
whereas for <u>semiconductors</u> it is narrow (d).

The Fermi energy for these two band structures lies within the band gap—near its center.

How does atomic band structure describe electronic conduction?

Only electrons with energies greater than the Fermi energy may be acted on and accelerated in the presence of an electric field.

These are the electrons that participate in the conduction process, which are termed **free electrons**.

Another charged electronic entity called a **hole** is found in semiconductors and insulators.

Holes have energies less than E_f and also participate in electronic conduction.

- Electrical conductivity is a direct function of the numbers of free electrons and holes.
- The distinction between conductors and nonconductors (insulators and semiconductors) lies in the numbers of these free electron and hole charge carriers.

For an electron to become free, it must be excited or promoted into one of the empty and available energy states above E_f.

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.

- In the presence of electric field, only a fraction are excited, this still gives rise to a relatively large number of free electrons and, consequently, a <u>high conductivity</u>.
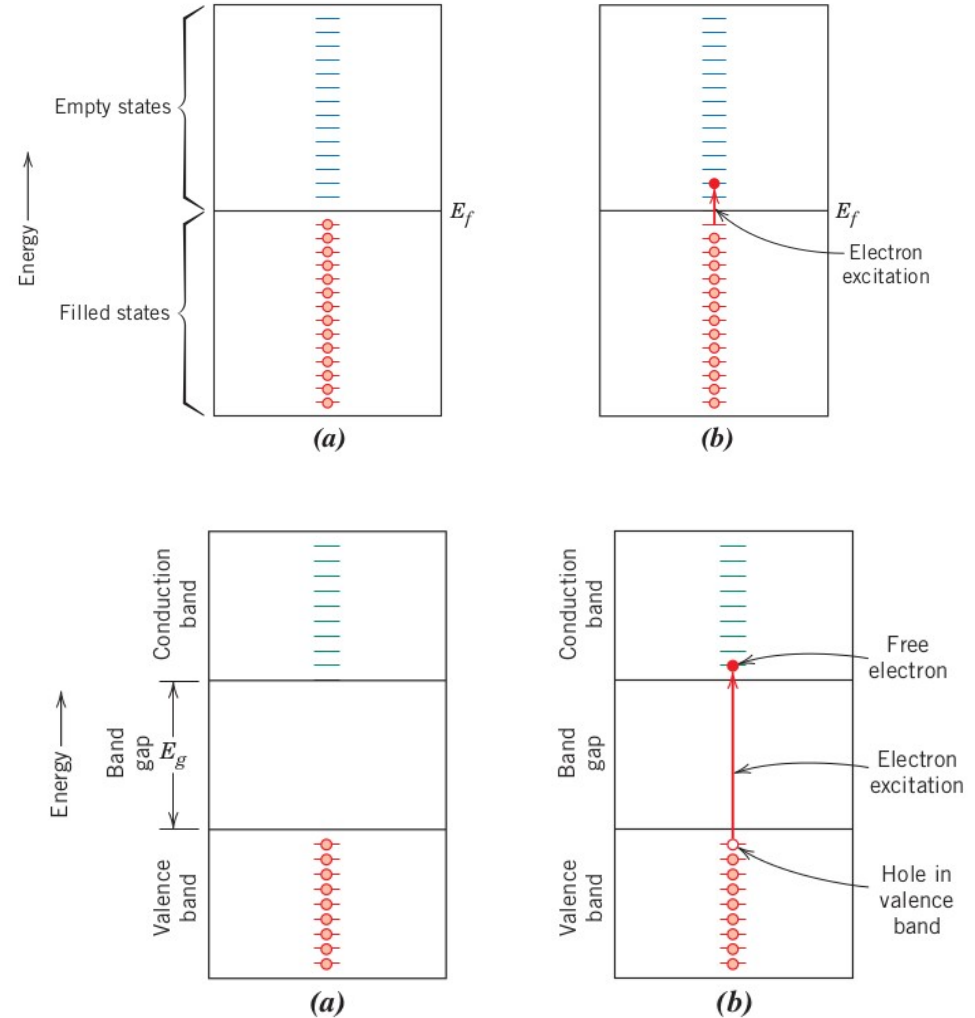
- For insulators and semiconductors, empty states adjacent to the top of the filled valence band are not available.

- To become free, therefore, 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.

Most often the excitation energy is from a nonelectrical source such as heat or light.

the larger the band gap, the lower the electrical conductivity at a given temperature.
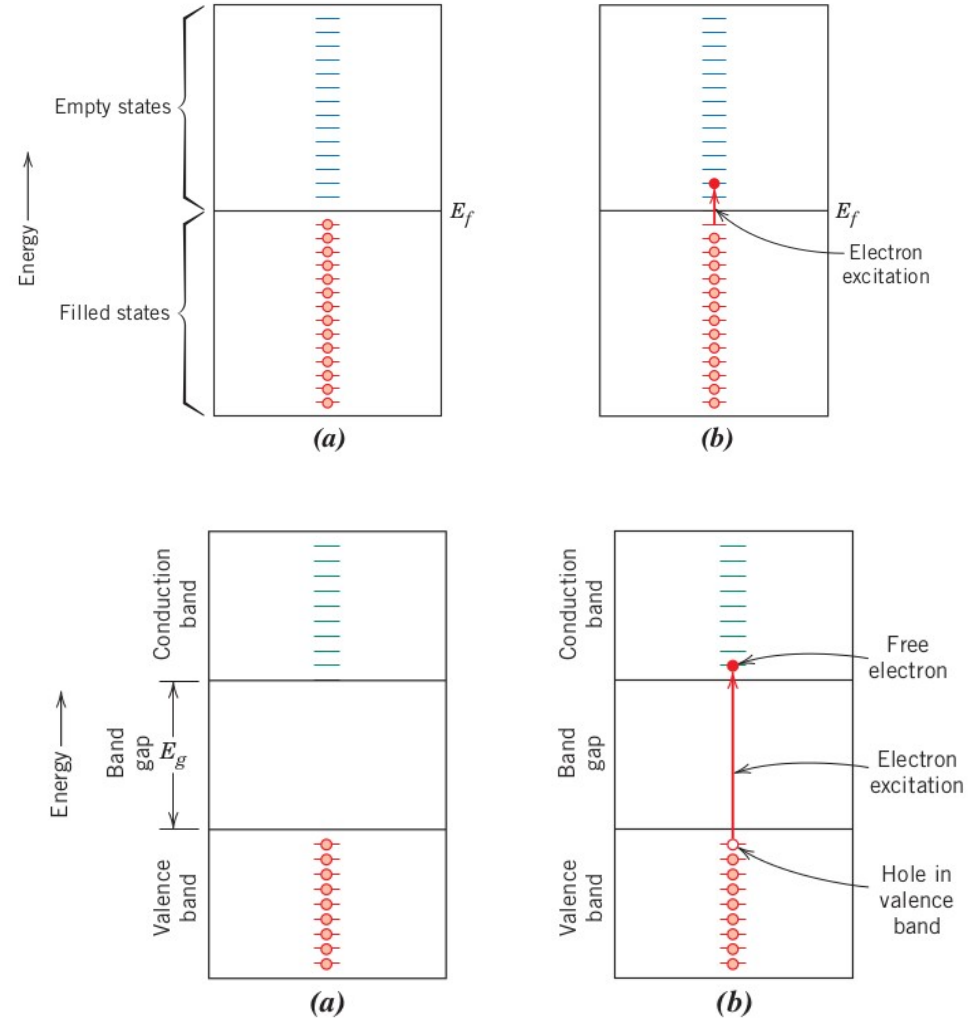
Distinction between semiconductors and insulators lies in the width of the band gap;

for semiconductors, it is narrow,
for insulating materials, it is relatively wide.

For electrically insulating materials, interatomic bonding is ionic or strongly covalent.
- The valence electrons are tightly bound to or shared with the individual atoms.
- these electrons are highly localized and are not in any sense free to wander throughout the crystal.

Bonding in semiconductors is covalent (or predominantly covalent) and relatively weak, which means that the valence electrons are not as strongly bound to the atoms.
- these electrons are more easily removed by thermal excitation than they are for insulators.

Electron mobility

- On application of electric field, a force is brought to bear on the free electrons;
- Hence, they all experience an acceleration in a direction opposite to that of the field.

- Under the condition of no interaction between an accelerating electron and atoms in a perfect crystal lattice, all the free electrons should accelerate with electric field, and electric current should continuously increase with time.

- However, a current reaches a constant value the instant that a field is applied.
- This indicates that there exist some frictional forces, which counter this acceleration from the external field.

- These frictional forces result from the scattering of electrons by imperfections in the crystal lattice, including impurity atoms, vacancies, interstitial atoms, dislocations, and even the thermal vibrations of the atoms themselves.
- Each scattering event causes an electron to lose kinetic energy and to change its direction of motion.

- There is some net electron motion in the direction opposite to the field, and this flow of charge is the electric current.

- Parameters that describe the extent of this scattering;
  - drift velocity and
  - mobility of an electron.

drift velocity $_d$: average electron velocity in the direction of the force imposed by the applied field. It is directly proportional to the electric field as:

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

The constant of proportionality μ_e is called the electron mobility. It is an indication of the frequency of scattering events; units: $m^2/V \cdot s$

Conductivity of most materials may be expressed as

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

n: number of free or conducting electrons per unit volume (e.g., per cubic Meter), and
|e| is the absolute magnitude of the electrical charge on an electron (1.6 × 10⁻¹⁹ C).

The electrical conductivity is proportional to both the number of free electrons and the electron mobility.

Numerical problem:

(a) Calculate the drift velocity of electrons in germanium at room temperature and when the magnitude of the electric field is 1000 V/m.

(b) Under these circumstances, how long does it take an electron to traverse a 25-mm (1-in.) length of crystal?

Charge Carriers in Insulators and Semiconductors
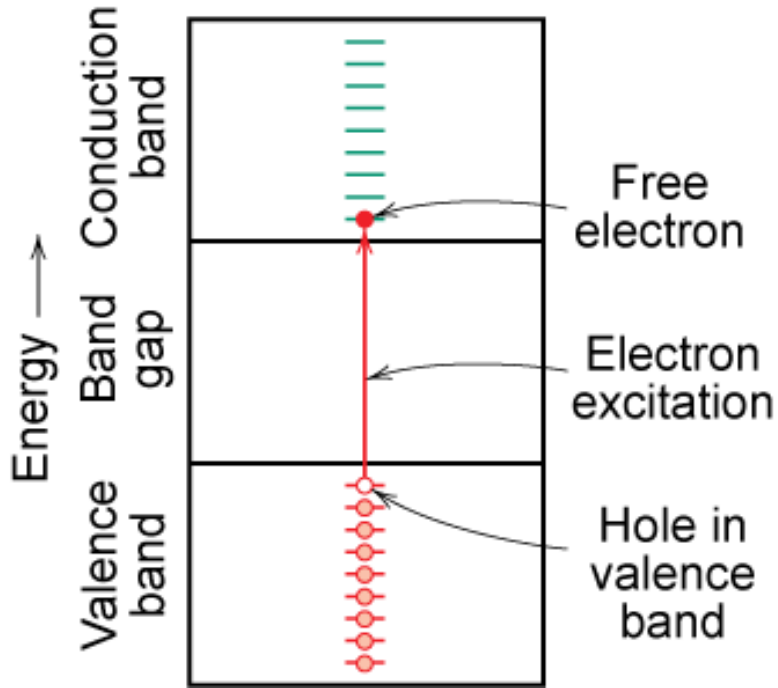
Two types of electronic charge carriers:

Free Electron
- negative charge
- in conduction band

Hole
- positive charge
- vacant electron state in the valence band

Semiconductivity

The electrical conductivity of semiconducting materials is not as high as that of metals. However, they have some unique electrical characteristics that render them especially useful.

The electrical properties of these materials are extremely sensitive to the presence of even minute concentrations of impurities.

Intrinsic semiconductors: the electrical behavior is based on the electronic structure inherent in the pure material.
Extrinsic semiconductors: When the electrical characteristics are dictated by impurity atoms.

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.
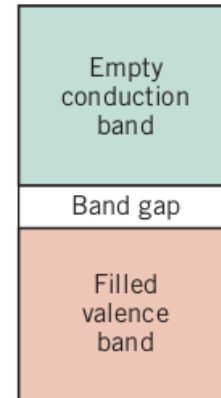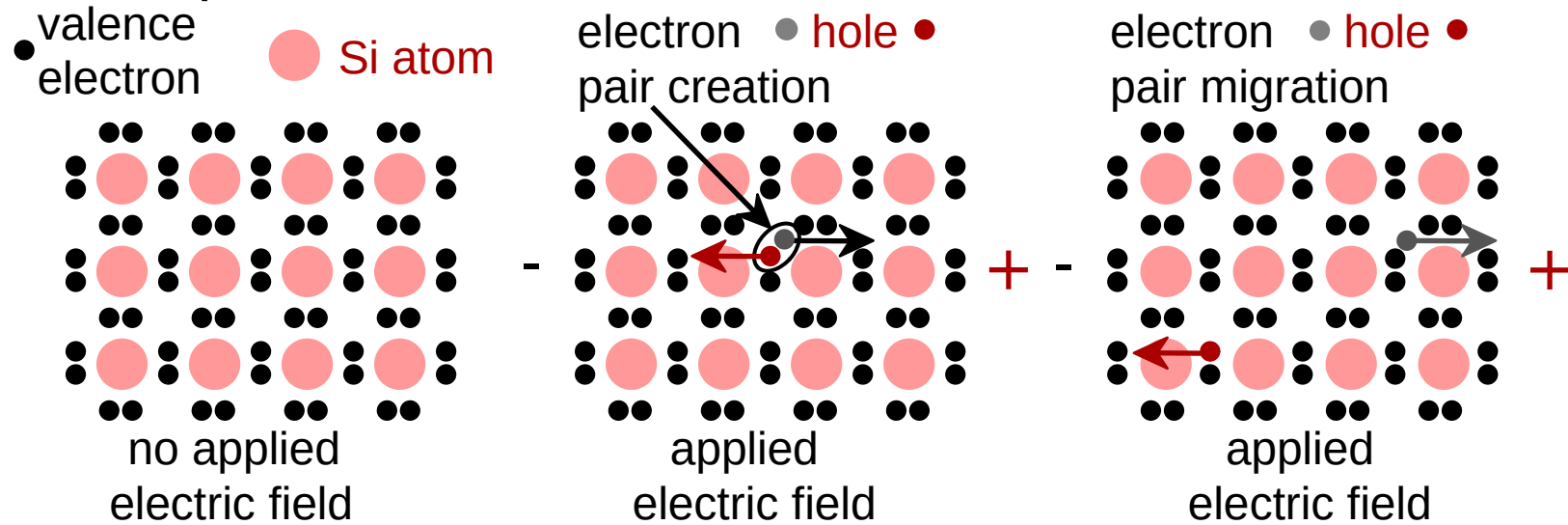
Intrinsic Semiconductors

- 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.

Intrinsic Semiconduction in Terms of Electron and Hole Migration

- Concept of electrons and holes:

- valence electron
- Si atom
- electron pair creation • hole •
- electron pair migration • hole •

no applied electric field

applied electric field

applied electric field

- 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

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

- for intrinsic semiconductor $n = p = n_i$

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

- Ex: GaAs

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

For GaAs $n_i = 4.8 \times 10^{24} \, m^{-3}$

Concept of a Hole

- In intrinsic semiconductors, for every electron excited into the conduction band, a missing electron is left behind in one of the covalent bonds.

- 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.

- It is conventional to treat 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 × 10^{-19} C).
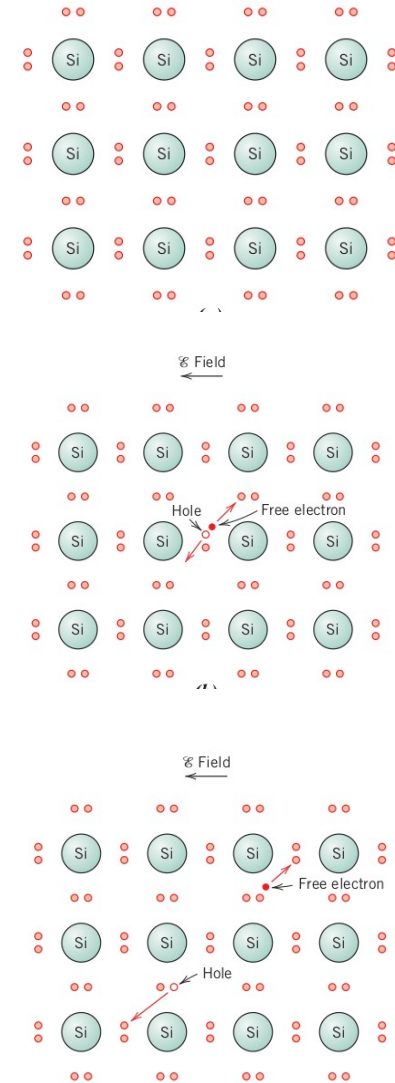
Semiconducting devices
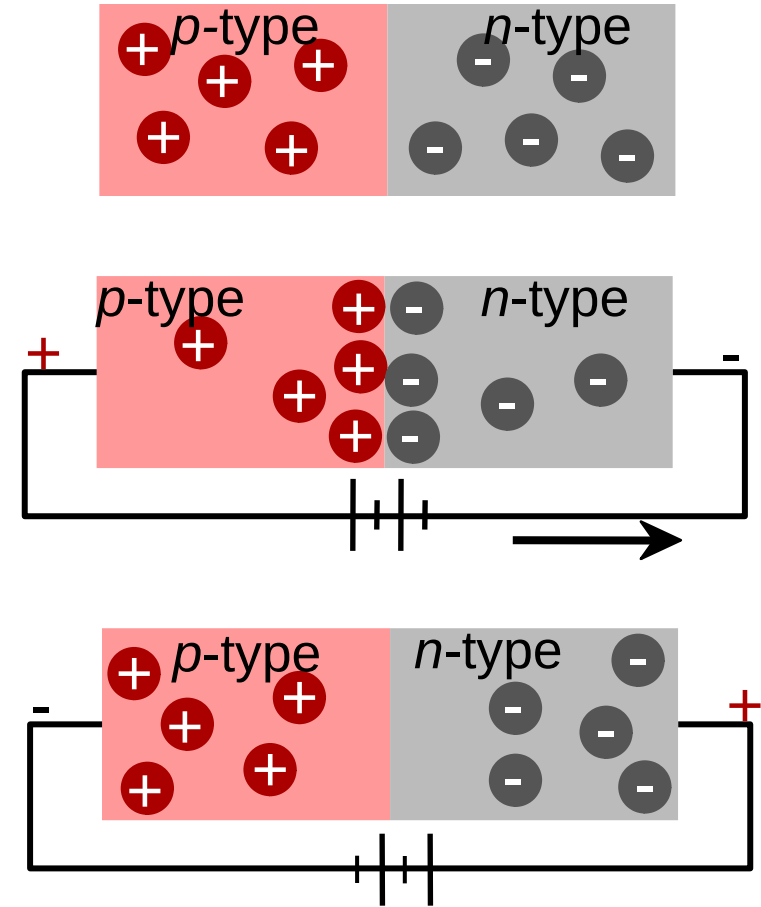
I. p-n Rectifying Junction

- p-n junction is created by combining an n-type material with a p-type.

- Initially both materials are neutral - When they come into contact, electrons from the n-type material will move into the holes of the p-type material

- This doesn't happen the other way though, because the electrons in the p-type material are at a lower energy than the holes of the n-type material)

- This creates a region known as the "**depletion layer**" - An electric field is created, in 1 direction, as a result of the charge separation

Direction of electric field

p-type   n-type   p-n Junction
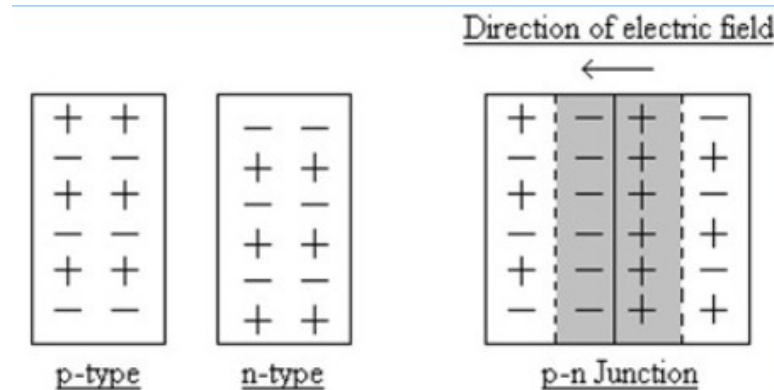
Biasing of the p-n junction

- Connect the positive terminal of the battery to the. p-type material and the negative terminal to the n-type.
- The free electrons in the n-type are repelled by the negative terminal while the holes of the p-type are repelled by the positive terminal.
- These meet at the junction, with electrons filling the holes
- Once the free electrons have been exhausted, the electrons from the circuit fill the holes, while the holes that they create are filled by others… current flows

- Connect the positive terminal to the n-type and the negative terminal to the p-type.
- The free electrons in the n-type are attracted towards the positive terminal, while the holes of the p-type are attracted towards the negative terminal.
- The electrons and holes thus move AWAY from the junction and therefore away from each other.
- this separation of positive and negative charges leaves the junction region relatively free of mobile charge carriers.
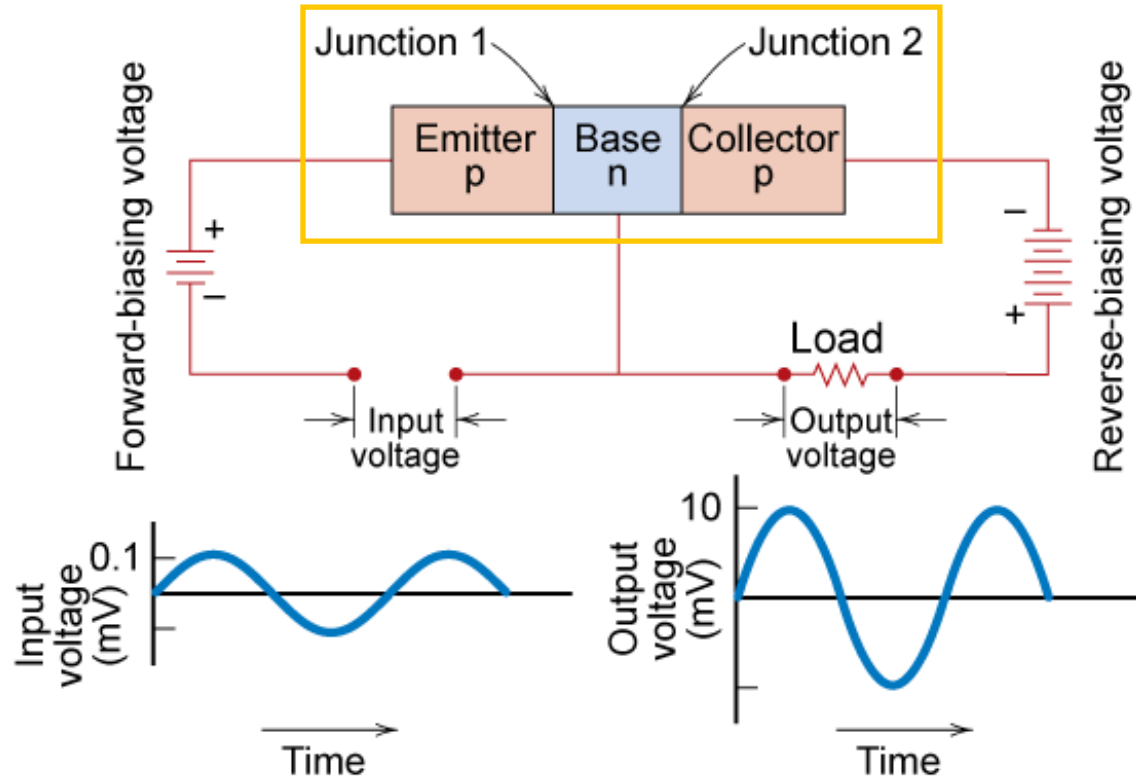
Applications

- 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.
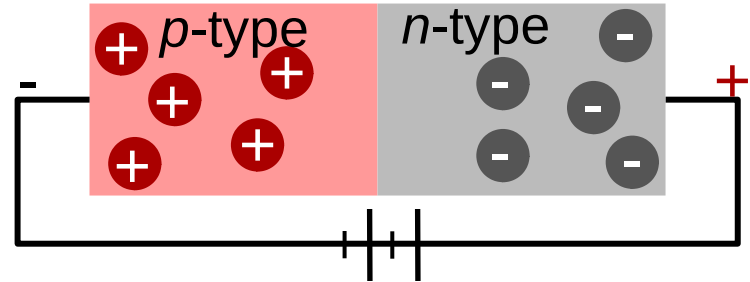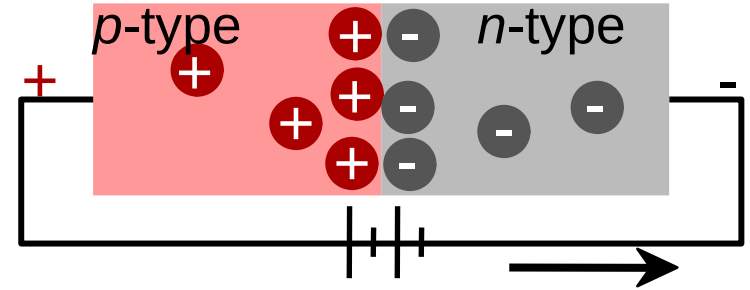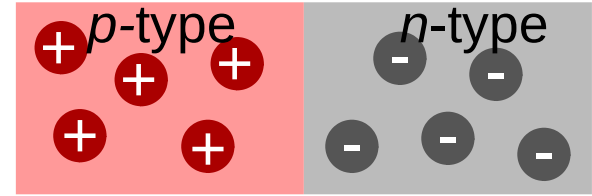
Properties of Rectifying Junction
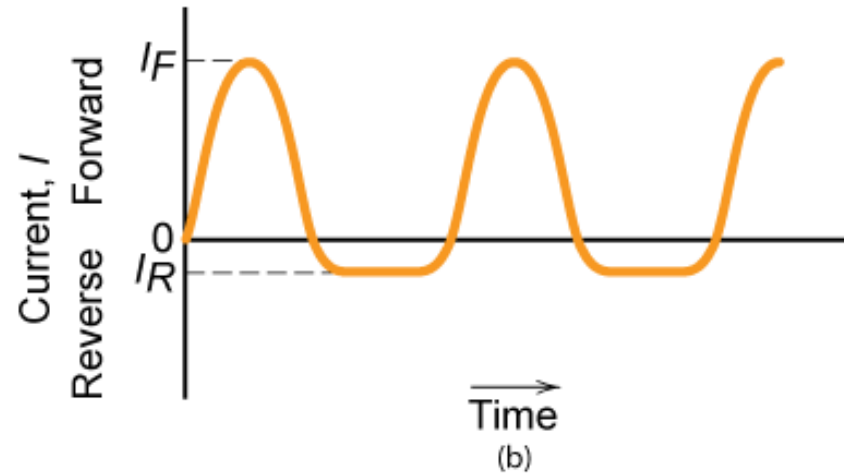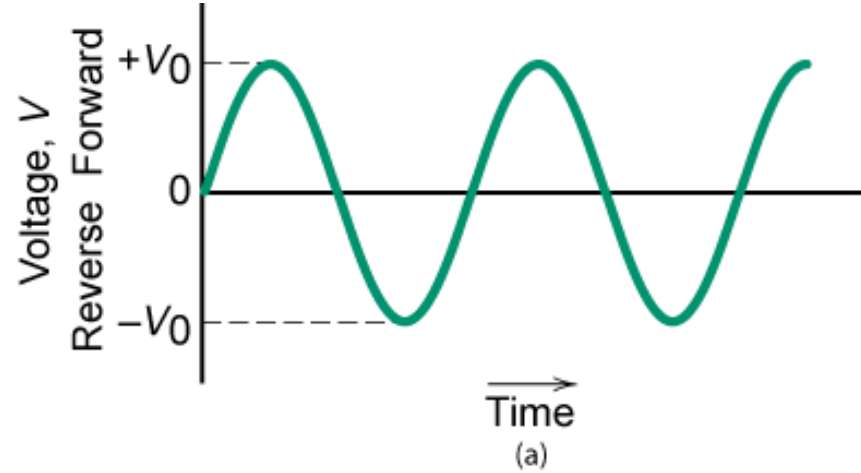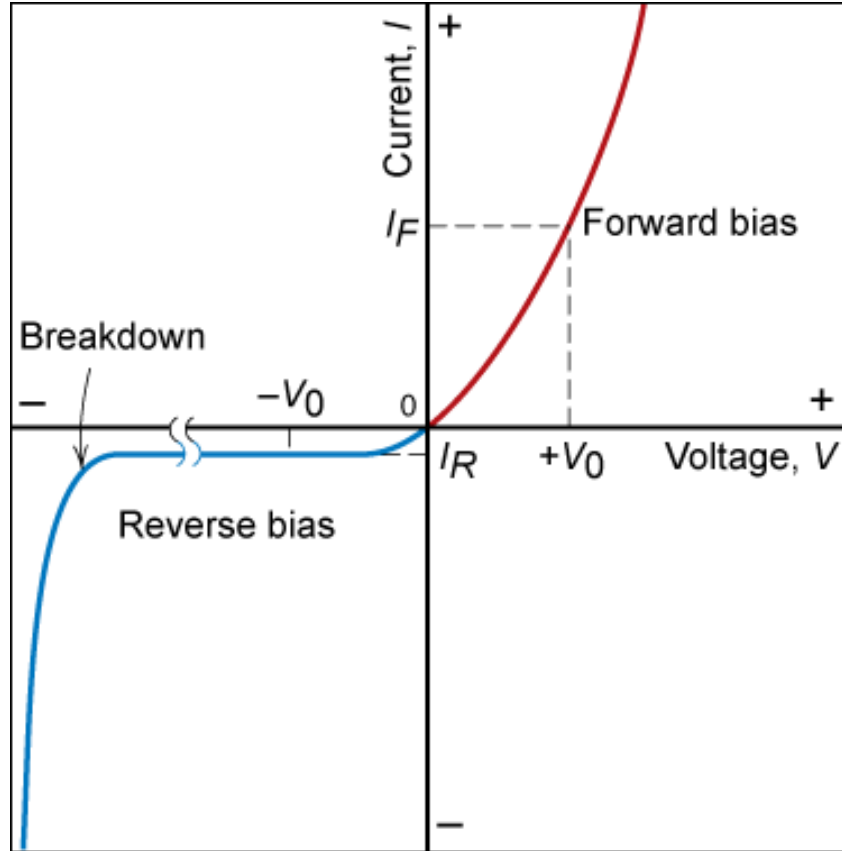
p–n–p Junction Transistor

- A very thin n-type base region is sandwiched between p-type emitter and collector regions.

- The circuit that includes the emitter–base junction (junction 1) is forward biased, whereas a reverse bias voltage is applied across the base–collector junction (junction 2).

- Because the emitter is p-type and junction 1 is forward biased, large numbers of holes enter the base region.

- These injected holes are minority carriers in the n-type base (and are energetically not very stable in the base region).

p–n–p Junction Transistor
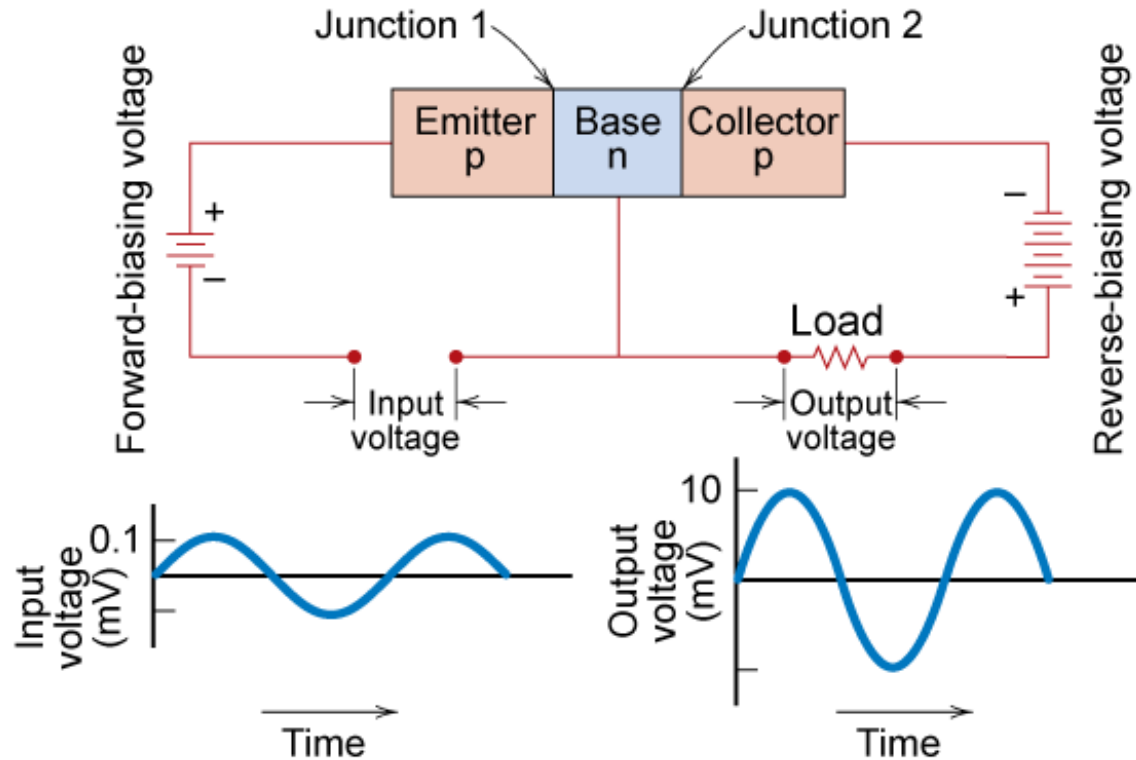
- Hence, most of the holes will be swept through the base without recombination, then across junction 2 and into the p-type collector.

- The holes now become a part of the emitter–collector circuit.

- A small increase in input voltage within the emitter–base circuit produces a large increase in current across junction 2.

- This large increase in collector current is also reflected by a large increase in voltage across the load resistor.

Thus, a voltage signal that passes through a junction transistor experiences an amplification.

Flash memory in computers

- Flash memory is programmed and erased electronically
- this flash technology is nonvolatile—that is, no electrical power is needed to retain the stored information.

- flash memory are attractive for general storage and transfer of data between portable devices, such as digital cameras, laptop computers, mobile phones, digital audio players, and game consoles.

- flash packages are extremely durable and are capable of withstanding relatively wide temperature extremes, as well as immersion in water.

Information is stored on a chip composed of a very large number of memory cells. Each cell consists of an array of transistors.

- ✓ Flash memory is a special type of electronically erasable, programmable, read-only memory (EEPROM).
- ✓ Data erasure is very rapid for entire blocks of cells, which makes this type of memory ideal for applications requiring frequent updates of large quantities of data.

Dielectric behaviour

A dielectric material is an electrically insulating (nonmetallic) material
• exhibits an electric dipole structure—that is, there is a separation of positive and negative electrically charged entities on a molecular or atomic level.
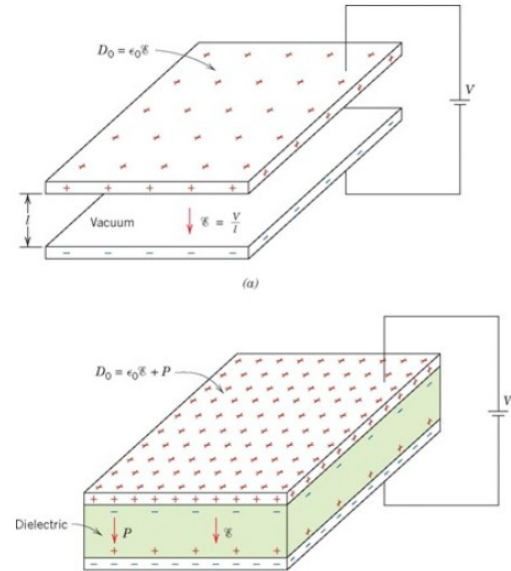
Capacitance

When a voltage is applied across a capacitor, one plate becomes positively charged and the other negatively charged, with the corresponding electric field directed from the positive to the negative plates.

The capacitance C is related to the quantity of charge stored on either plate Q by

$$C = \frac{Q}{V}$$

where V is the voltage applied across the capacitor. The units of capacitance are cou-lombs per volt, or farads (F).

In a a parallel-plate capacitor with a vacuum in the region between the plates, the capacitance may be computed from the relationship

$$C = \varepsilon_0 \frac{A}{l}$$

where A represents the area of the plates and l is the distance between them. The parameter ε_0, called the permittivity of a vacuum, is a universal constant having the value of 8.85 × 10^{-12} F/m.

If a dielectric material is inserted into the region within the plates, then

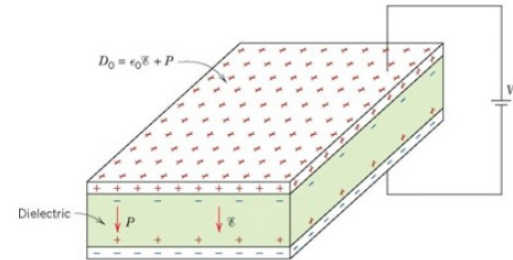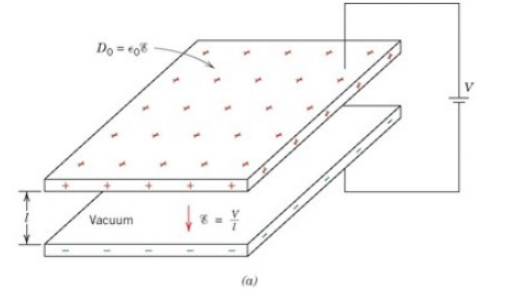$$C = \varepsilon \frac{A}{l}$$

where is the permittivity of this dielectric medium, which is greater in magnitude than ε_0.
The relative permittivity ε_r is called the dielectric constant,

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

ε_r is greater than unity and represents the increase in charge-storing capacity upon insertion of the dielectric medium between the plates.

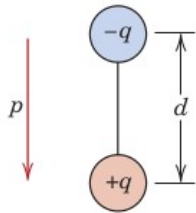| Material	Dielectric Constant	
	60 Hz	1 MHz
	Ceramics	
Titanate ceramics	—	15–10,000
Mica	—	5.4–8.7
Steatite (MgO–SiO_2)	—	5.5–7.5
Soda–lime glass	6.9	6.9
Porcelain	6.0	6.0
Fused silica	4.0	3.8
	Polymers	
Phenol-formaldehyde	5.3	4.8
Nylon 6,6	4.0	3.6
Polystyrene	2.6	2.6
Polyethylene	2.3	2.3
Polytetrafluoroethylene	2.1	2.1

Dielectric constants for some dielectric materials

Field vectors and polarization

For every electric dipole generated by two electric charges (positive and negative), separated by the distance d, there is a dipole moment.

An electric dipole moment p is associated with each dipole is given as: $p = qd$

where q is the magnitude of each dipole charge and d is the distance of separation be-tween them.

- A dipole moment is a vector that is directed from the negative to the positive charge.
- In the presence of an electric field $\mathcal{E}$, which is also a vector quantity, a force (or torque) comes to bear on an electric dipole to orient it with the applied field.
- The process of dipole alignment is termed **polarization**.

An electric dipole.
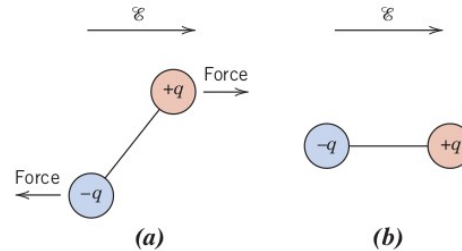
Under applied electric field $\mathcal{E}$

# How is the dielectric constant related to polarization?

In the capacitor, the surface charge density D, or quantity of charge
per unit area of capacitor plate (C/m^2), is proportional to the electric field.
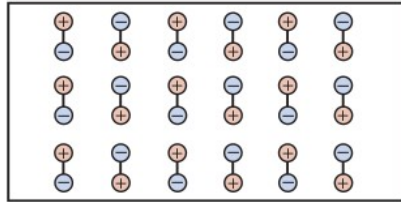
- Under vacuum conditions, $D_0 = \varepsilon_0 \mathscr{E}$

  where the constant of proportionality is ε_0.

- Analogous expression exists for the dielectric case $D = \varepsilon_0 \mathscr{E} + P$

- D is also called the dielectric displacement, and P is the polarization, or the increase in charge density above that for a vacuum because of the presence of the dielectric.

- The polarization P may also be thought of as the total dipole moment per unit volume of the dielectric material, or as a polarization electric field within the dielectric that results from the mutual alignment of the many atomic or molecular dipoles with the externally applied field $\mathscr{E}$.
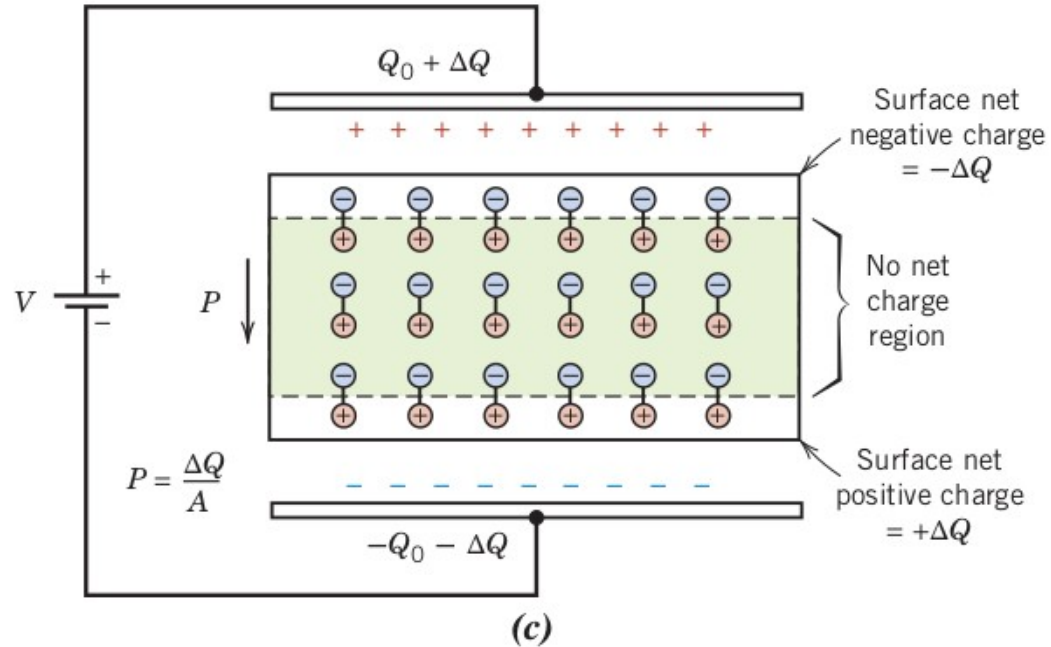
Dielectric constant and polarization

(a)
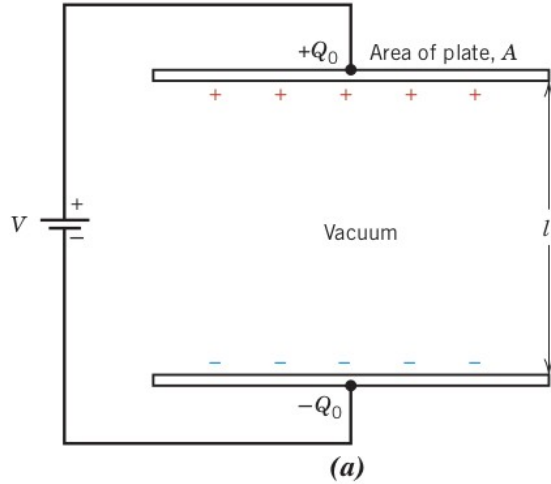
charge stored on capacitor plates for a vacuum

$+Q_0$ Area of plate, A

V

Vacuum l

$-Q_0$

(b)

dipole arrangement in an unpolarized dielectric

$Q_0 + \Delta Q$

V P

$P = \dfrac{\Delta Q}{A}$

$-Q_0 - \Delta Q$

Surface net negative charge $= -\Delta Q$

No net charge region

Surface net positive charge $= +\Delta Q$

(c)

the increased charge-storing capacity resulting from the polarization of a dielectric material.

Consider a parallel-plate capacitor having an area of 6.45×10^{-4} m^2 (1 in.^{2}) and a plate separation of 2×10^{-3} m (0.08 in.) across which a potential of 10 V is applied. If a material having a dielectric constant of 6.0 is positioned within the region between the plates, compute the following:
(a) The capacitance
(b) The magnitude of the charge stored on each plate
(c) The dielectric displacement D
(d) The polarization

Frequency dependence of dielectric constant

- In many practical situations, the current is alternating (ac)—that is, an applied voltage or electric field changes direction with time.
- Consider a dielectric material that is subject to polarization by an ac electric field.
- With each direction reversal, the dipoles attempt to reorient with the field.
- This process requires some finite time.
- Some minimum reorientation time exists that depends on the ease with which the particular dipoles are capable of realignment.
- The relaxation frequency is taken as the reciprocal of this minimum reorientation time.

A dipole cannot keep shifting orientation direction when the frequency of the applied electric field exceeds its relaxation frequency, and, therefore, it will not make a contribution to the dielectric constant.
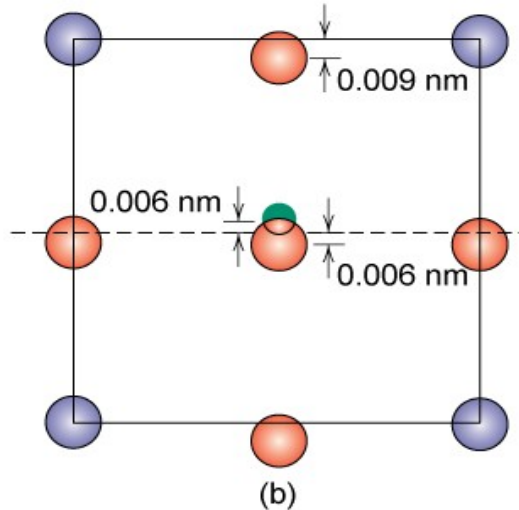
(a)

(b)
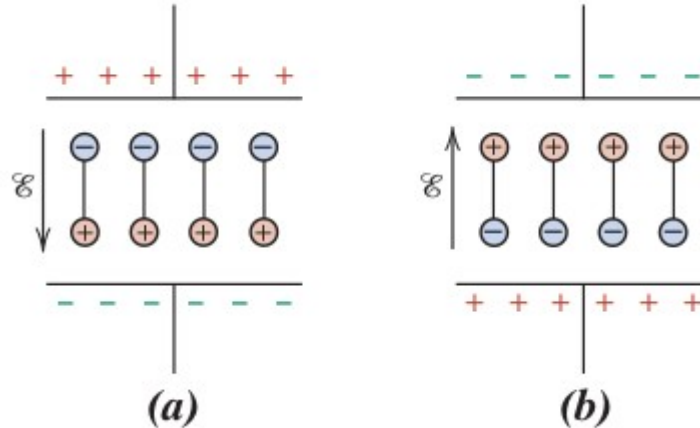
Ferroelectric Ceramics

Experience spontaneous polarization - polarization in the absence of an electric field.
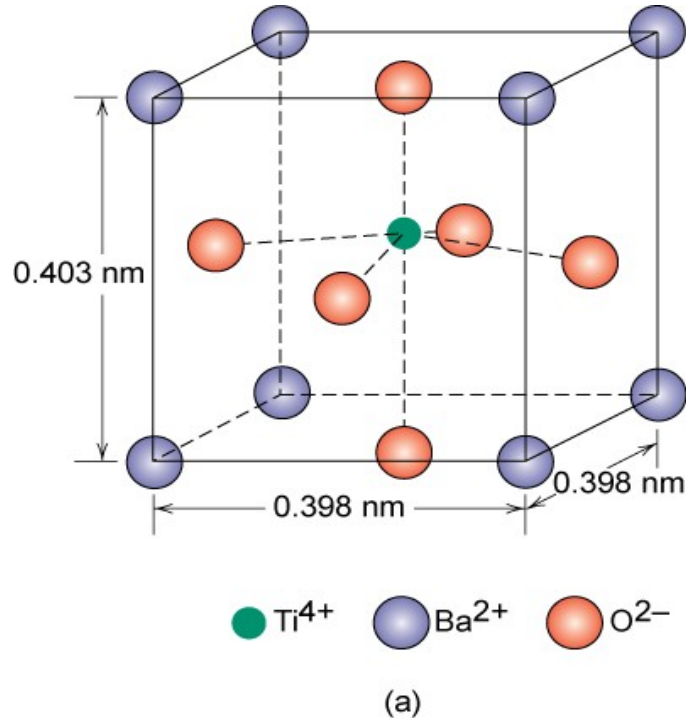
BaTiO$_3$ -- ferroelectric below its Curie temperature (120°C)

0.403 nm

0.398 nm

0.398 nm

● Ti^{4+} ● Ba^{2+} ● O^{2-}

(a)

0.009 nm

0.006 nm

0.006 nm

(b)

Spontaneous polarization of this group of materials results as a consequence of interactions between adjacent permanent dipoles in which they mutually align, all in the same direction.

- A number of ceramics and polymers are used as insulators and/or in capacitors.

- Glass, porcelain, steatite, and mica, have dielectric constants within the range of 6 to 10 These materials also exhibit a high degree of dimensional stability and mechanical strength.

- Ferroelectrics have extremely high dielectric constants at relatively low applied field frequencies; for example, at room temperature, ε r for barium titanate may be as high as 5000.

  Name a few ferroelectric materials.

Piezoelectric Materials

Piezoelectricity

- application of stress induces voltage
- Reversing the sign of the force (e.g., from tension to compression) reverses the direction of the field.
- application of voltage induces dimensional change

Name a few piezo-electric materials.

stress-free   with applied stress