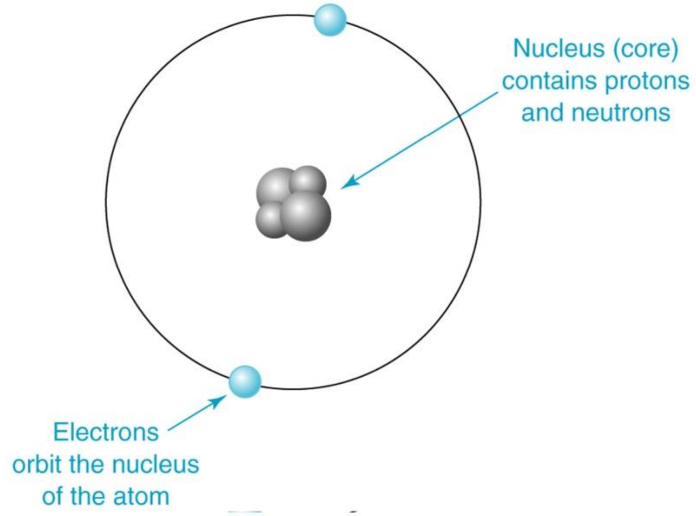
Semiconductors

Atomic Structure

- Atom – smallest particle of matter that retains the physical characteristics of an element
- Atomic Number of an Atom – number of protons
- Atoms contain an equal number of protons and electrons
- Bohr Model
  - Simplest model of an atom
  - Central core (nucleus) – contains protons and neutrons
  - Electrons revolve around nucleus

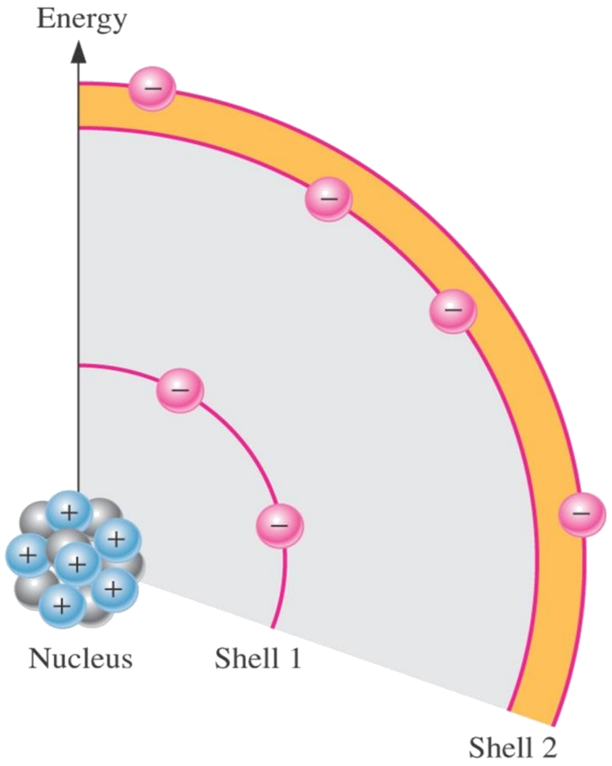


Atomic Structure

- Electrons go around the nucleus in their **orbits**
- Each orbit has some energy level
- Group of orbits called **shell**
- Electrons on the same shell have similar energy level
- Number of electrons (N) on each shell (n)

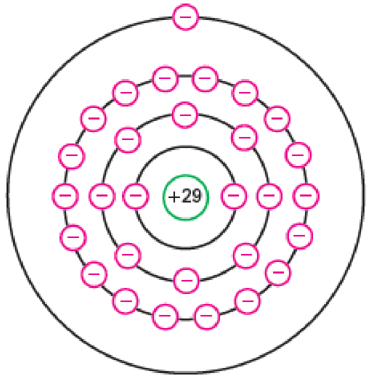
$$N = 2n^2$$

  - First shell has 2 electrons
  - Second shell has 8 electrons

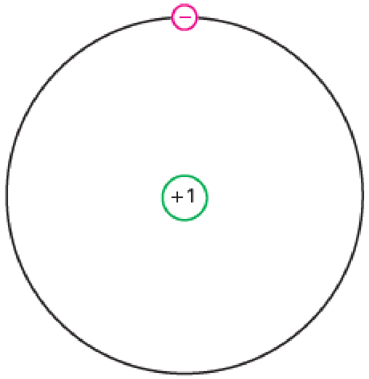


Valence Shell

- Atoms are made of valence shell and core
- Valence shell is the outermost shell
- Valence shell has valence electrons ready to be freed
- This orbit controls the electrical properties of the atom.
- *Core* of an atom is the nucleus and all the inner orbits
- When an atom has more of one particle than the other the atom acquires the charge of the greater.
  - + Ion, Has more Protons than Electrons,
  - - Ion, Has more Electrons than Protons**.**



Copper atom.



Core diagram of copper atom.

Solid-state electronic materials

- Electronic materials fall into three categories with respect to resistivity
  - Insulators $\rho > 10^5\ \Omega$-cm (diamond $\rho = 10^{16}$)
  - Semiconductors $10^{-3} < \rho < 10^5\ \Omega$-cm
  - Conductors $\rho < 10^{-3}\ \Omega$-cm (copper $\rho = 10^{-6}$)

- In order of conductivity:
  - Conductors
  - Semiconductors
  - Insulators

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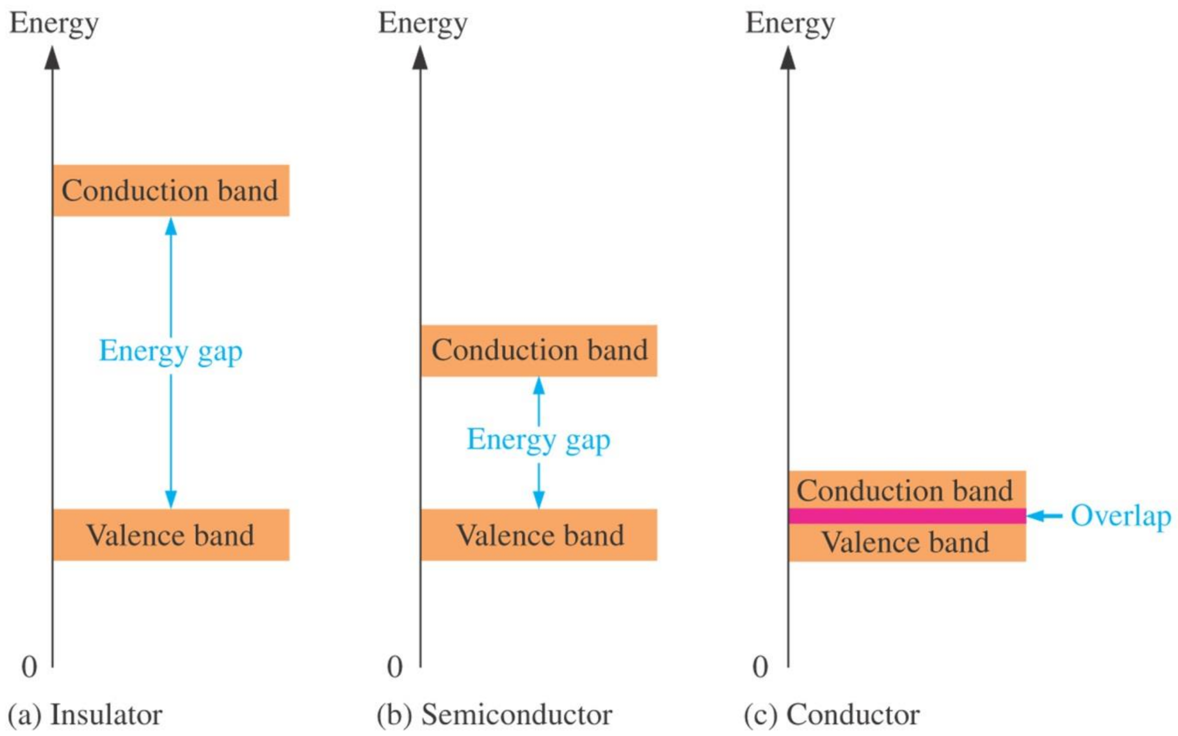
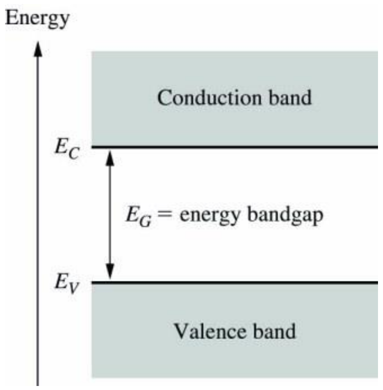
Solid-state electronic materials

- Bandgap is an energy range in a solid where no electron states can exist.
- It refers to the energy difference between the top of the valence band and the bottom of the conduction band





Conductors

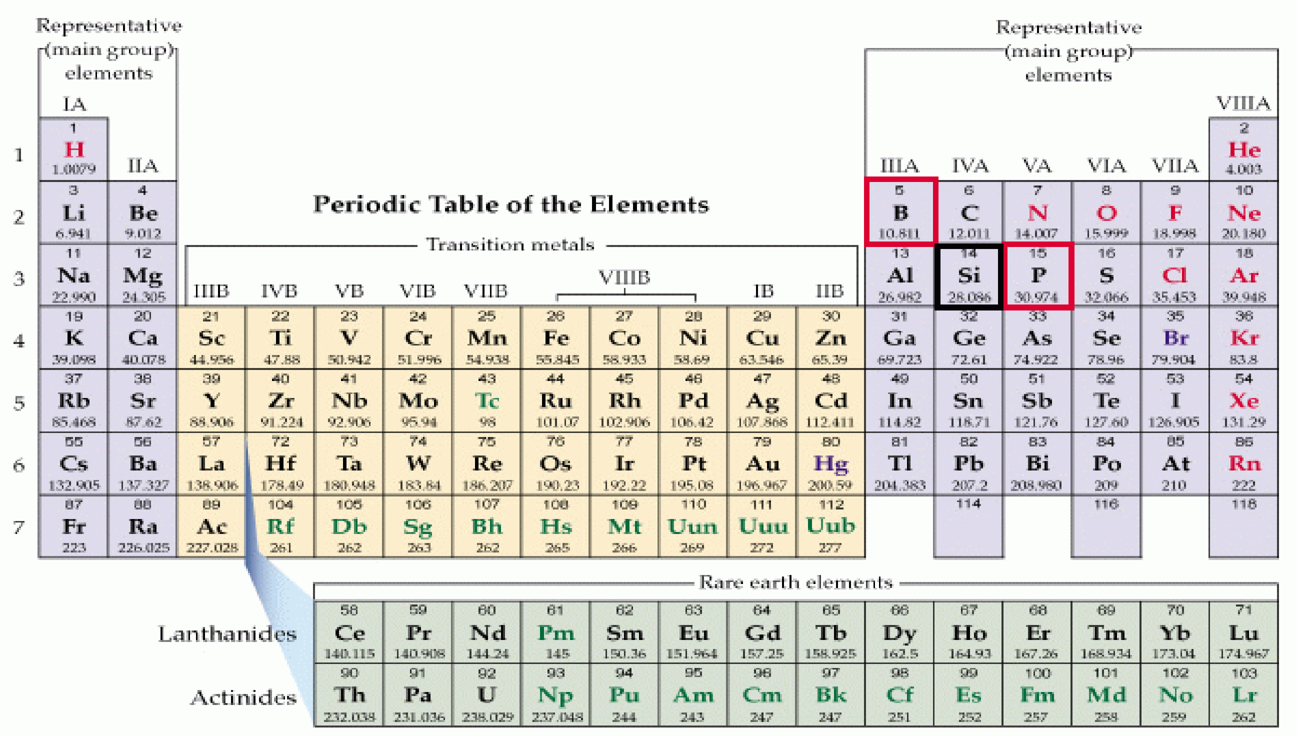
- Material capable of carrying electric current, i.e. material which has "mobile charge carriers" (e.g. electrons, ions..)
- Has loosely bound electrons in its outer or Valence shell, they are easily displaced
- Have a high concentration of electrons in *conduction bands* e.g. metals, liquids with ions (water, molten ionic compounds)
- Current is carried by a single type of mobile charge, the free electron (current carrier).
- There is relatively large density of mobile charge carriers.

Insulators

- Materials with no or very few free charge carriers
- Has tightly bound electrons in its outer or Valence ring, they are not easily displaced.
- Have virtually zero electrons in bands
  - conduction band energy is too high
  - all the electrons are stuck in *valance bands*
- Eg: quartz, most covalent and ionic solids, plastics

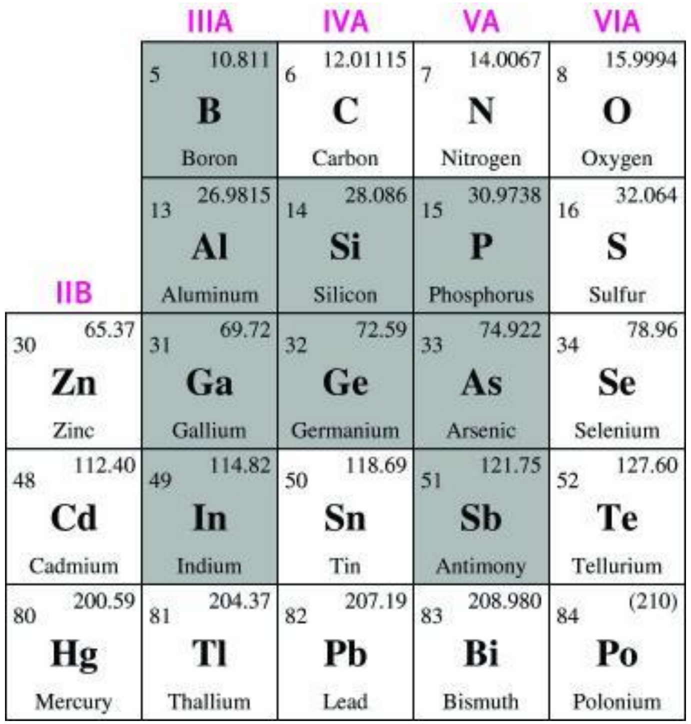
Semiconductors

- Elemental semiconductors are formed from a single type of atom of column IV, typically Silicon.
- Compound semiconductors are formed from combinations of elements of column III and V or columns II and VI.



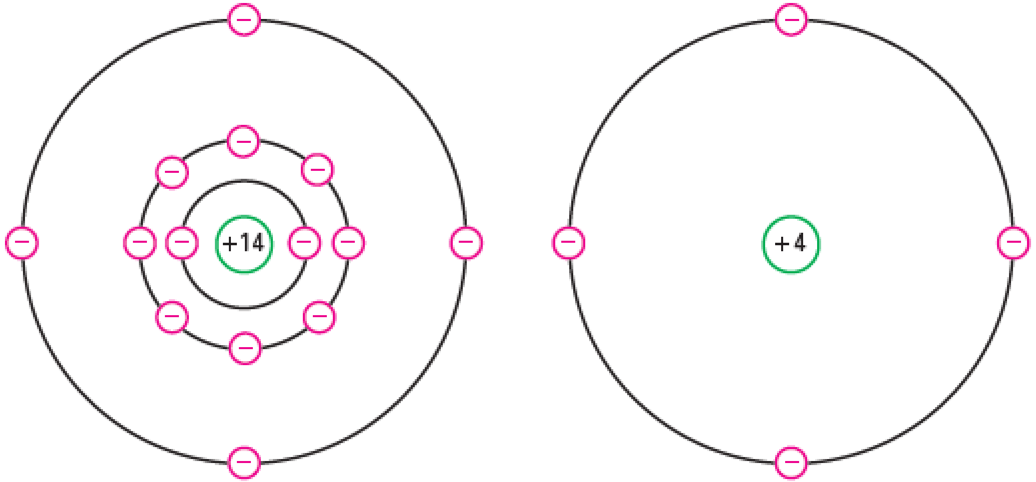
Semiconductor Materials

Semiconductor	Bandgap Energy E_G (eV)
Carbon (diamond)	5.47
Silicon	1.12
Germanium	0.66
Tin	0.082
Gallium arsenide	1.42
Gallium nitride	3.49
Indium phosphide	1.35
Boron nitride	7.50
Silicon carbide	3.26
Cadmium selenide	1.70



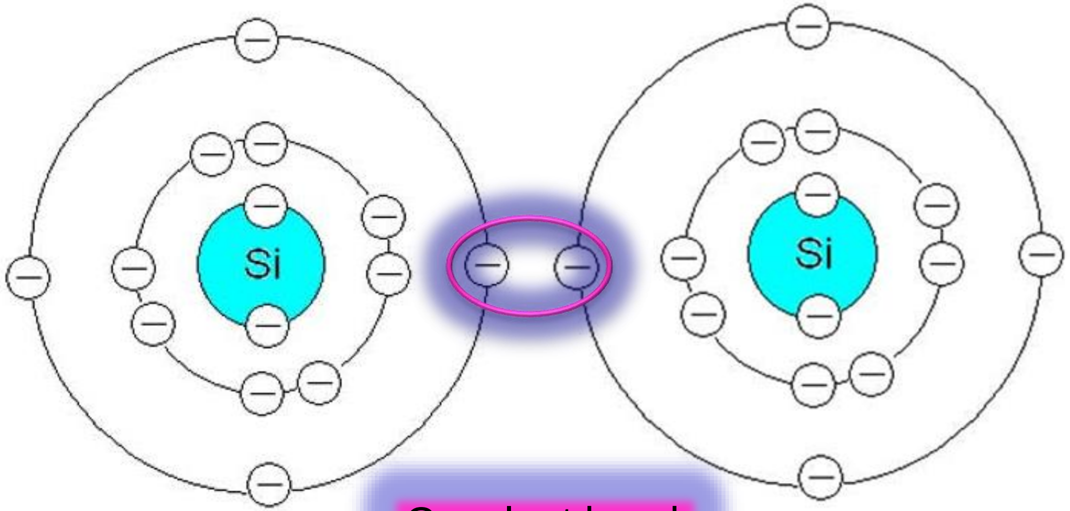
Intrinsic Silicon

- Intrinsic refers to properties of pure materials.



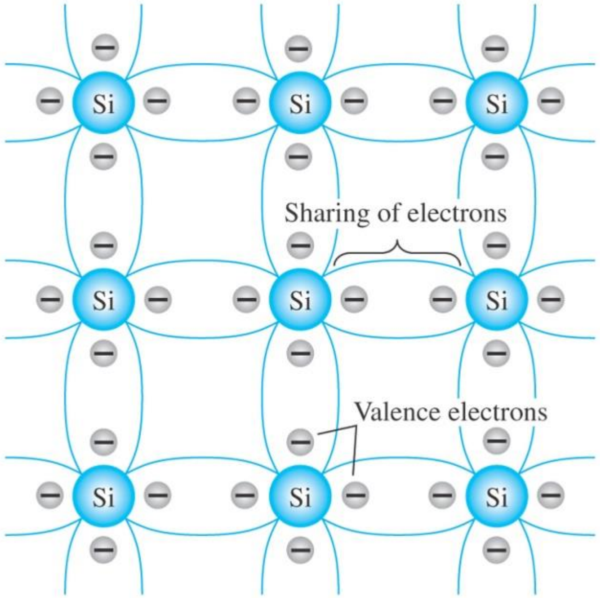
Intrinsic Silicon

- Covalent Bonding

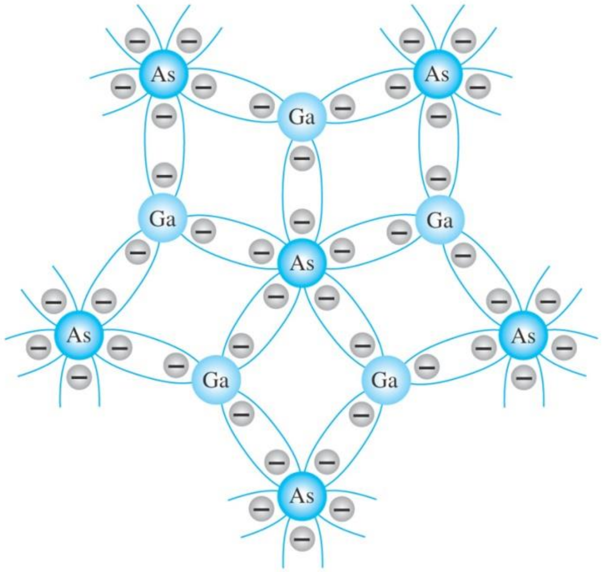


Covalent bond

Covalent Bonding



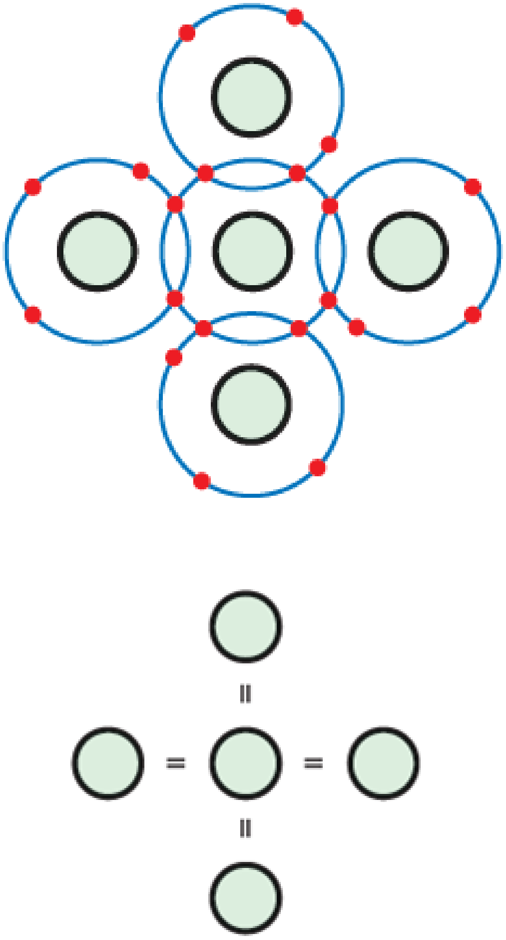
Covalent bonding of Si crystal



Covalent bonding of GaAs crystal

This bonding of atoms, strengthened by the sharing of electrons, is called covalent bonding

Intrinsic Silicon

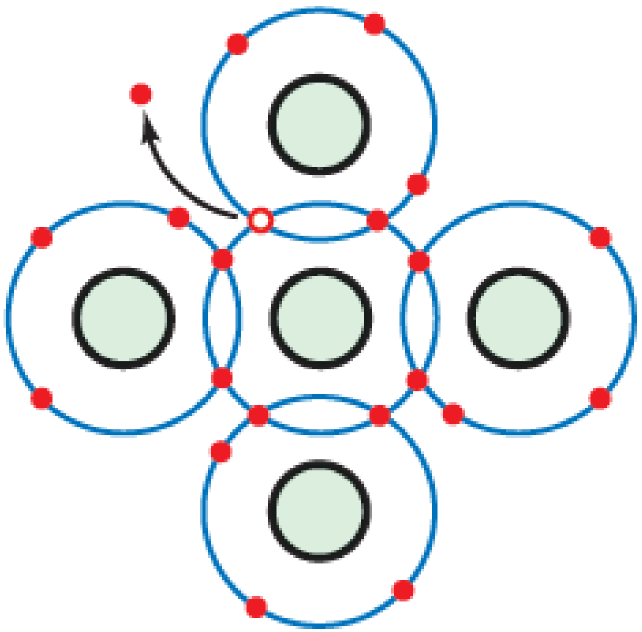


- Near absolute zero, all bonds are complete
- Each Si atom contributes one electron to each of the four bond pairs
- The outer shell is full, no free electrons, silicon crystal is an insulator

- What happens as the temperature increases?

Intrinsic Silicon

When temperature increases



- Increasing temperature adds energy to the system and breaks bonds in the lattice, generating electron-hole pairs.
- The departure of the electron creates a vacancy in the valence orbit called a **hole**
- Some of the electrons can fall into the holes – recombination.
- **Recombination** is the merging of a free electron and a hole.

Intrinsic Semiconductors

- **intrinsic semiconductor** – is one which is not doped
  - One example is pure silicon.
- **generation** – is the process of free electrons and holes being created.
  - **generation rate** – is speed with which this occurs.
- **recombination** – is the process of free electrons and holes disappearing.
  - **recombination rate** – is speed with which this occurs.

Generation may be effected by **thermal energy**. As such, both generation and recombination rates will be a function of temperature.

Intrinsic Semiconductors

- **Thermal generation** – effects a equal concentration of free electrons and holes.
  - Therefore, electrons move randomly throughout the material.
- In thermal equilibrium, generation and recombination rates are equal.
- Concentration of free electrons is equal to the concentration of holes

Intrinsic carrier concentration

- Concentration of free electrons is equal to the concentration of holes

$$n = p = n_i$$

$$n_i = BT^{3/2} e^{-E_g/2kT}$$

- n_i = number of free electrons and holes in a unit volume for intrinsic semiconductor
- B = parameter which is 7.3 x 10^{15} $cm^{-3}K^{-3/2}$ for silicon
- T = temperature (K)
- E_g = bandgap energy which is 1.12 eV for silicon
- k = Boltzman constant (8.62 x 10^{-5} eV/K)

Electron-Hole Concentration

- The electron density is n
- Hole density is represented by p.
- For intrinsic silicon, $n = n_i = p$.
- The product of electron and hole concentrations is

$$pn = n_i^2$$

- The pn product above holds when a semiconductor is in thermal equilibrium (not with an external voltage applied).

Semiconductor doping

- Doping is the process of adding very small well controlled amounts of impurities into a semiconductor.

- Doping enables the control of the resistivity and other properties over a wide range of values.

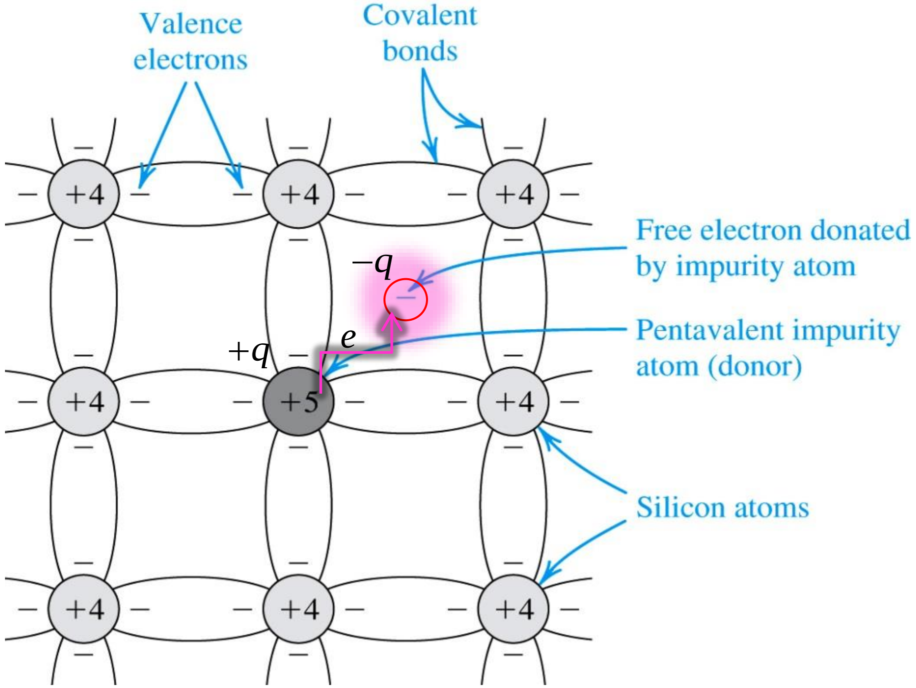
- Increase conductivity of a semiconductor

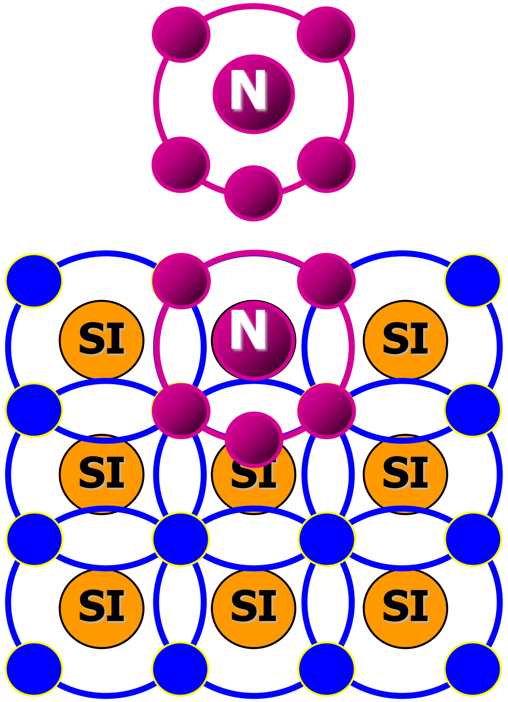
- For silicon, impurities are from columns III and V of the periodic table.

- Extrinsic - Impure semiconductors obtained by adding impurities

Donor Impurities in Silicon

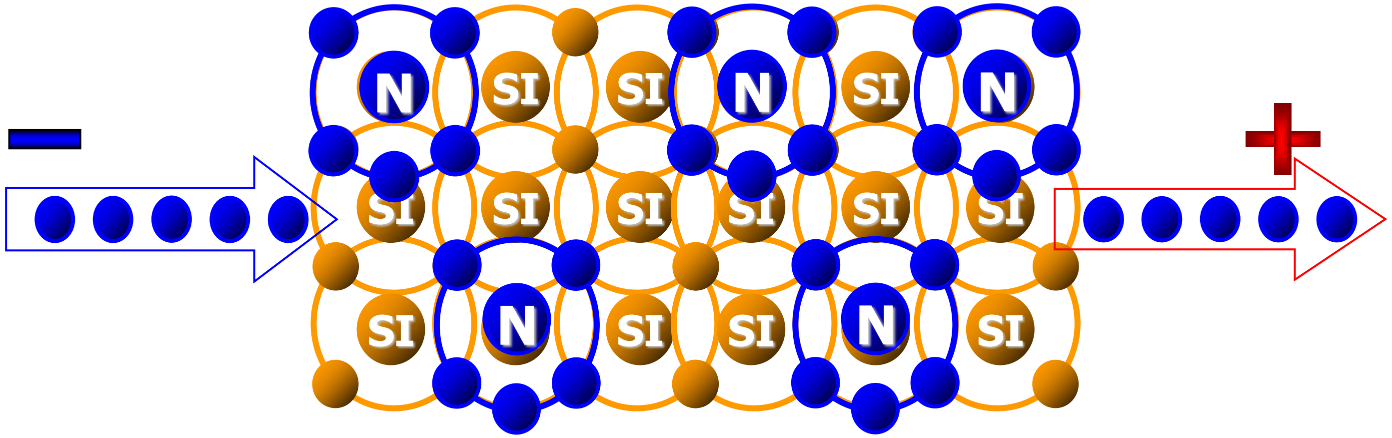
- Pentavalent Doping – Donor Material
- Pentavalent material have five outer shell electrons, there is now an ‘extra’ electron in the structure
- Increases concentration of electrons
- Group V elements - Phosphorous, Arsenic, and Antimony





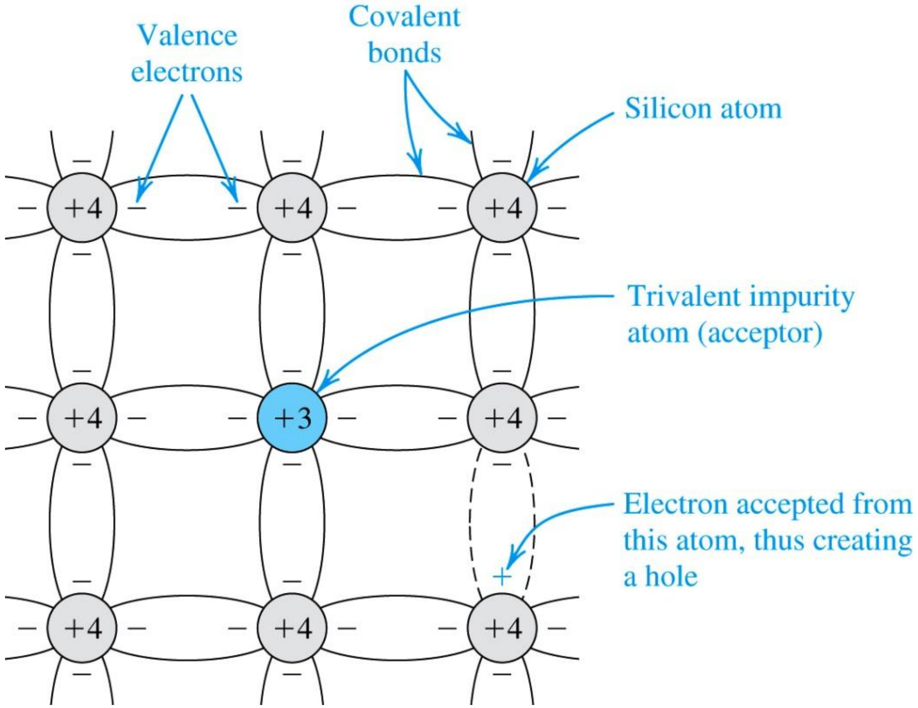
N-type Semiconductor

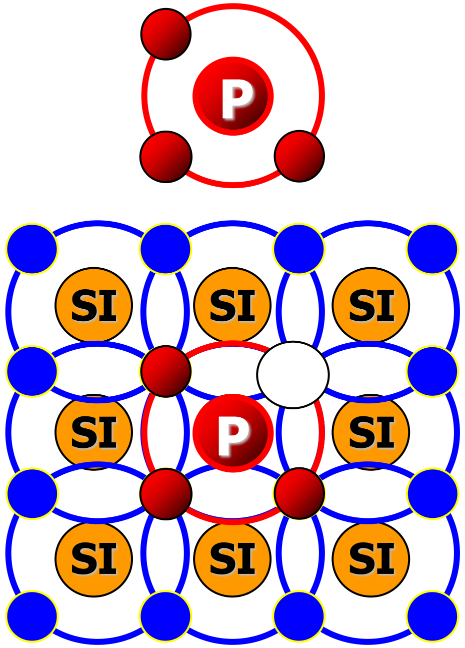
- Free electrons outnumber the holes in an n-type semiconductor
- Free electrons are called **majority carriers**
- Holes are called **minority carriers**
- Negative charge



Acceptor Impurities in Silicon

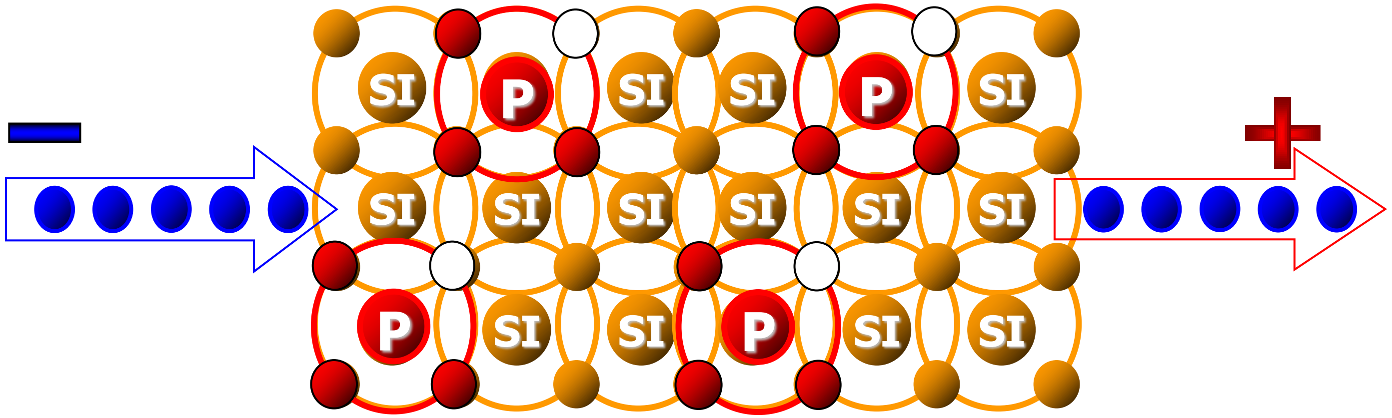
- Trivalent Doping - Acceptor Material.
- Trivalent atoms have only three valence electrons – there is one ‘hole’ in the structure
- Increases concentration of holes
- Group III elements - Boron, Aluminum, and Gallium





P-type Semiconductor

- Holes outnumber free electrons
- Holes are referred to as the majority carriers
- Free electrons are known as the minority carriers
- Positive charge



Summary

- In doped material, the electron and hole concentrations are no longer equal.
- If ***n* > *p***, the material is ***n*-type**.
- If ***p* > *n***, the material is ***p*-type**.
- Carrier with largest concentration is **majority carrier**
- Carrier with smallest concentration is **minority carrier**