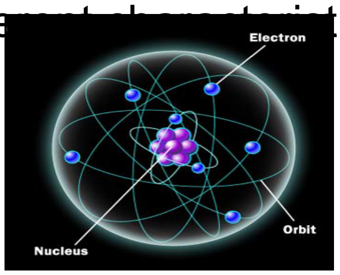
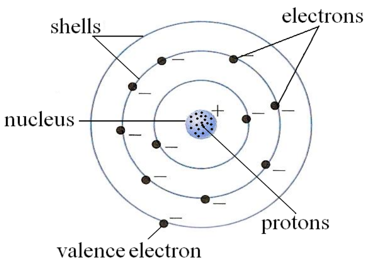
COE/EE 152 – Lecture 2

- Outline
  - Nature of the atom.
  - Basic Concepts of semiconductor charge carriers.
  - Energy bands.
  - Intrinsic and Extrinsic semiconductors.
  - Carrier Transport: Diffusion current, drift current. mobility, conductivity and resistivity
  - Generation and recombination of carriers
- Recommended reading
  - Microelectronic Circuit Design by Jaeger and Blalock

Nature of the Atom

- Everything in the universe is made up of atoms
- Consists of protons, electrons and neutrons
- Atoms in different elements differ in the number constituents which accounts for their different characteristics





Nature of the Atom

- Each electron has a mass of 9.11×10^{-31} kg and a negative charge of 1.602×10^{-19} C
- Each proton has a mass of 1.673×10^{-27} kg and an equal but opposite charge to that of an electron
- The mass of a neutron is approximately the same as that of a proton

Nature of the Atom

- Since the weight of the neutron and neutron are much bigger that the electron,
  - *Atomic weight = no. of protons + no. of neutrons*
- The atomic number is either the no. of protons or electrons
- No. of electrons in an orbit is given by 2n2

Valence Electrons

- Valence electrons determine the physical and chemical property of a material
- The outermost orbit can have a maximum of 8 valence electrons
    - Metals conductors have valence electrons less than 4
    - Insulators have valence electrons more than 4
    - Semiconductors have 4 valence electrons. Meaning they have both metallic and non-metallic properties. (e.g silicon, carbon, germanium)

Periodic Table of Elements

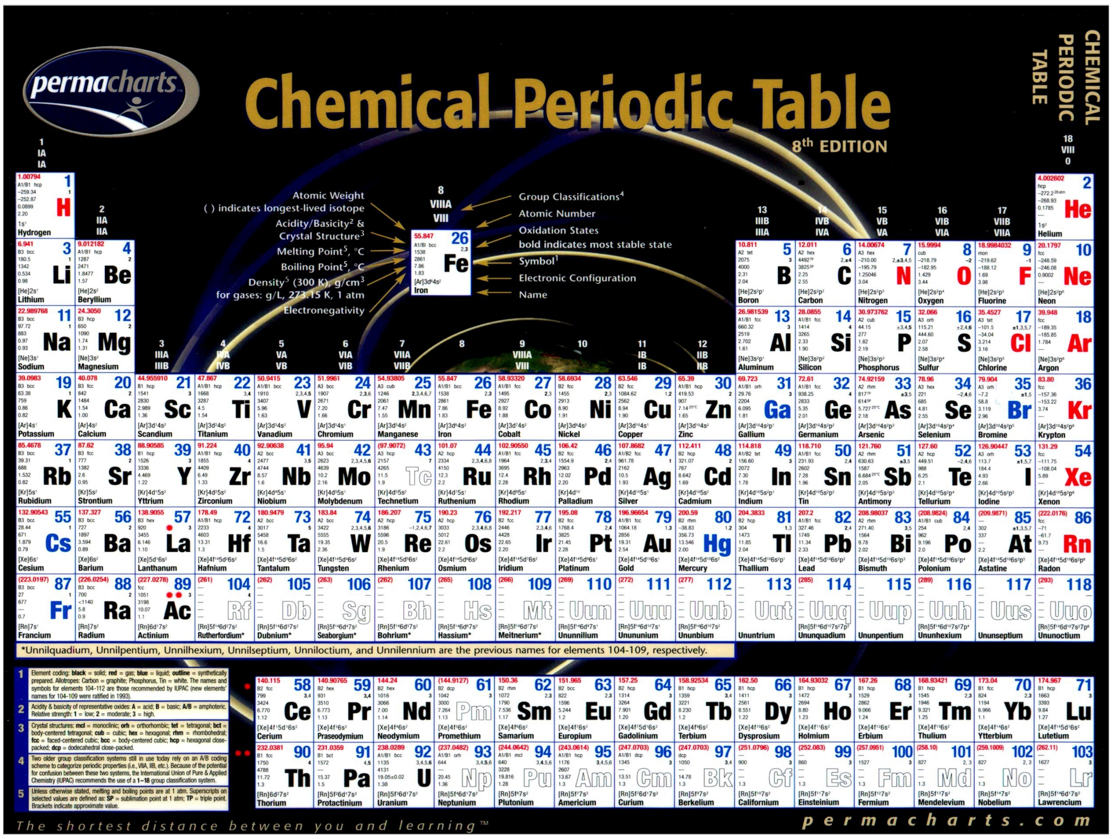
- Elemental Semiconductors are formed from Group IV of the periodic table
- Compound semiconductors are formed from a combination of Group II and VI or Group III and V
    - These materials are referred to as II-VI (2-6) or III-V (3-5) compound semiconductors

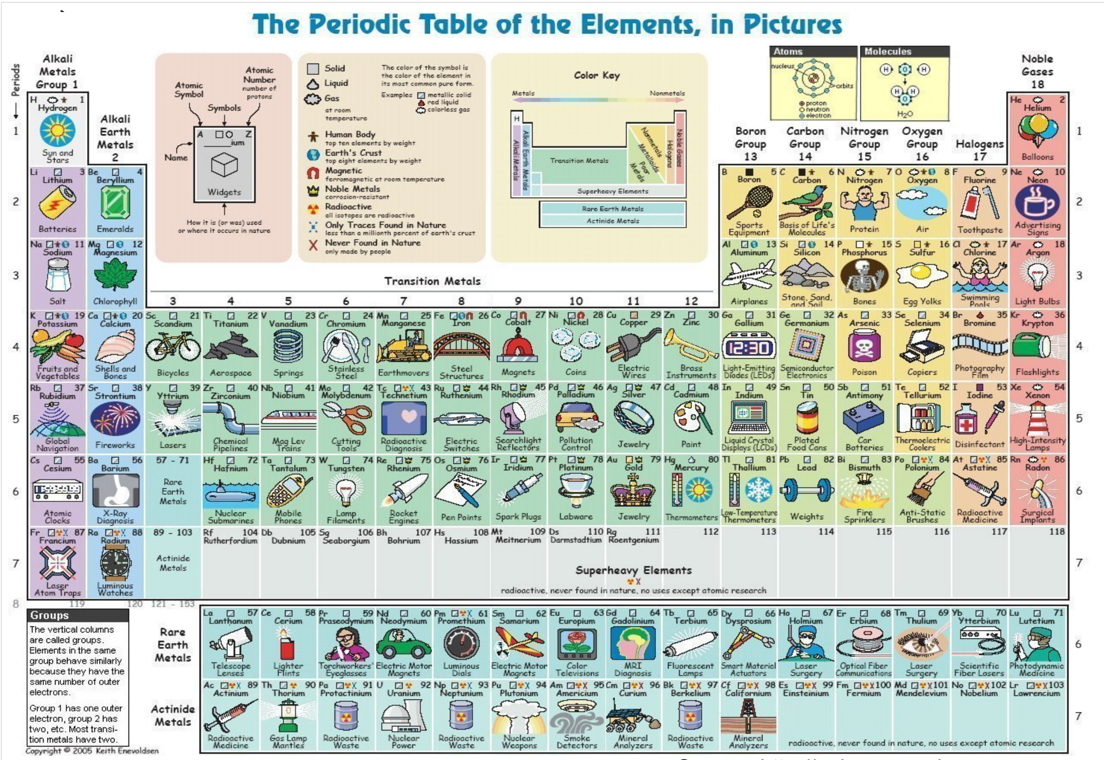
Group II	*Group III*	*Group IV*	*Group V*	*Group VI*
	B **Boron** 5	C **Carbon** 6	N **Nitrogen** 7	O **Oxygen** 8
Mg **Magnesium** 12	Al **Aluminium** 13	Si **Silicon** 14	P **Phosphorus** 15	S **Sulphur** 16
Zn **Zinc** 30	Ga **Gallium** 31	Ge **Germanium** 32	As **Arsenic** 33	Se **Selenium** 34
Cd **Cadmium** 48	In **Indium** 49	Sn **Tin** 50	Sb **Antimony** 51	Te **Tellurium** 52
Hg **Mercury** 80	Tl **Thallium** 81			

III–V

II–VI

Source: http://www.iue.tuwien.ac.at/phd/palankovski/node18.html



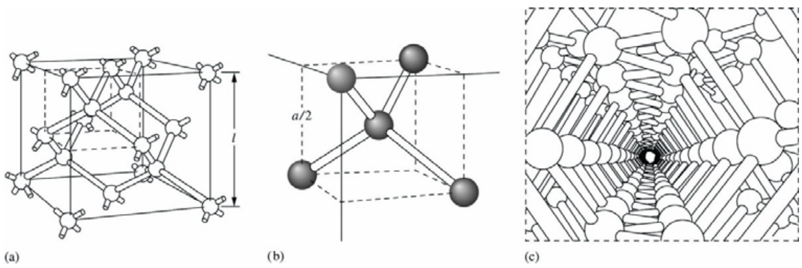


Source: http://universe-review.ca

Covalent Bond Model

- Atoms bond together in ***amorphous, polycrystalline or single-crystal forms***
  - Amorphous materials have a disordered structure
  - Polycrystalline materials consists of a large number of small crystallites
  - Single-crystal materials consists of one large crystal with regular shape
- Semiconductors (e.g silicon) has 4 valence electrons which forms a single crystal by covalent bonding of each atom

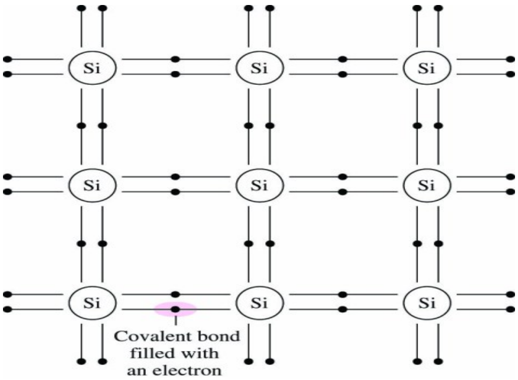
Crystal Lattice Structure



- Crystal lattice structure of solid state materials

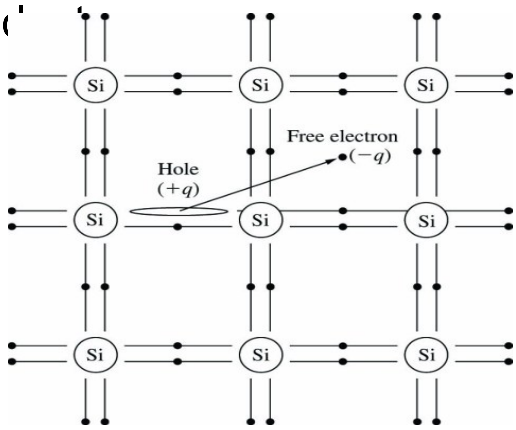
Covalent Bonding

- For temperatures approaching 0K, all covalent bonds are intact and no free electron to conduct and therefore an insulator



Covalent Bonding

- A small amount of ***electron-hole*** pairs are generated when a covalent bond is broken as the temperature is increased and therefore free to cond



Intrinsic Carrier Density, $n_i(cm^{-3})$

- Intrinsic refers to the generic properties of the pure material
- Intrinsic carrier density is the density of free electrons at a particular temperature

$$n_i^2 = BT^3 e^{\frac{-E_G}{KT}} cm^{-6}$$

where:

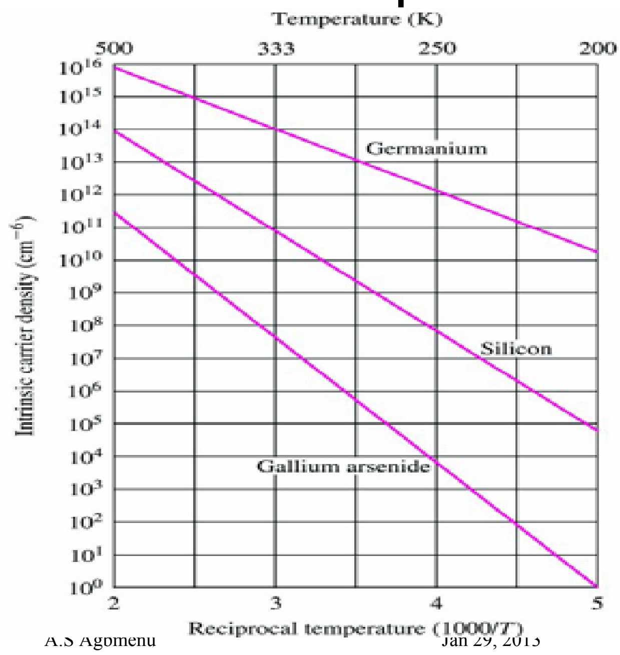
$E_G = semiconductor\ bandgap\ energy, eV$

$k = Boltzmann's\ constant, 8.62 \times 10^{-5}\ eV/K$

$T = absolute\ temperature, K$

$B = material\ dependent\ parameter, 1.08 \times 10^{31} cm^{-6}\ for\ Si$

Intrinsic Carrier Density vs. Temperature

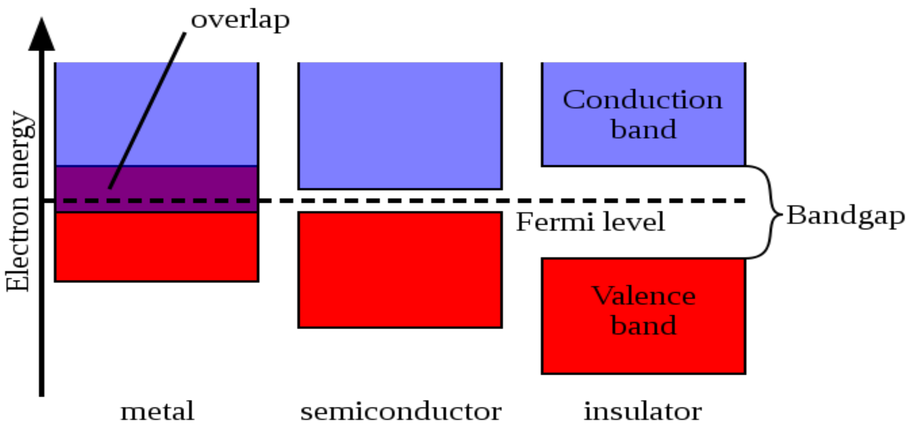


	B ($K^{-3} \cdot cm^{-6}$)	E_G (eV)
Si	1.08×10^{31}	1.12
Ge	2.31×10^{30}	0.66
GaAs	1.27×10^{29}	1.42

Energy Band Model

- For a material to conduct, electrons have to move from the valence band to the conduction band
- At absolute zero (0K), electrons occupy the valence band and can only gain enough energy to get as high as the Fermi level
- Electrons are free to conduct when they are in the conduction band
- The minimum amount of energy required to reach the conduction band is the ***bandgap enegy***

Energy Band Model

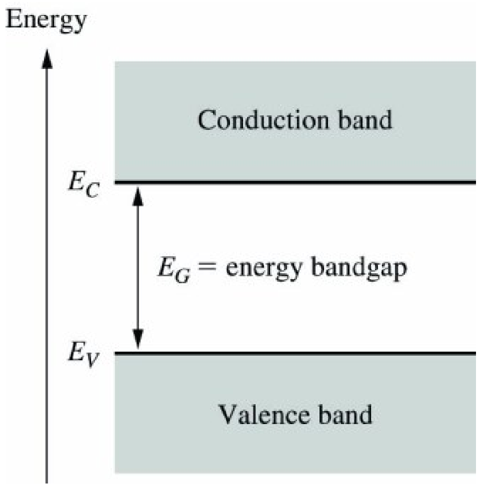


Energy band model for various solids

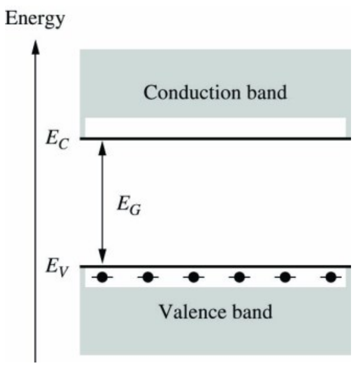
Energy Band Model

- E_V is the top edge of the valence band representing the highest possible energy of the valence electron
- E_C represents the lowest available energy for the conduction band
- E_G is the energy bandgap or the forbidden gap energy

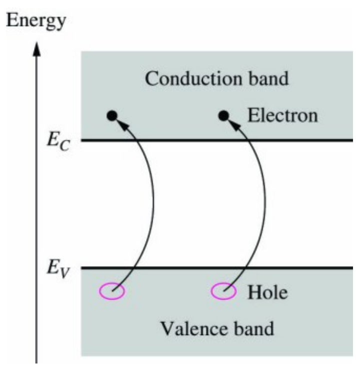
$$E_G = E_C - E_V$$



Energy band Model



T = 0K



T > 0K

Carrier Mobility, μ

- Mobility is a measure of hoe easily a carrier moves in a material
- Charged particles move in response to an electric field
- This movement is termed ***drift*** which results in current flow called ***drift current***

Carrier Mobility, μ

- Positive charges (holes) drift in the same direction as the electric field
- Negative charges (electrons) drift in the opposite direction

Drift Velocity is therefore defined:

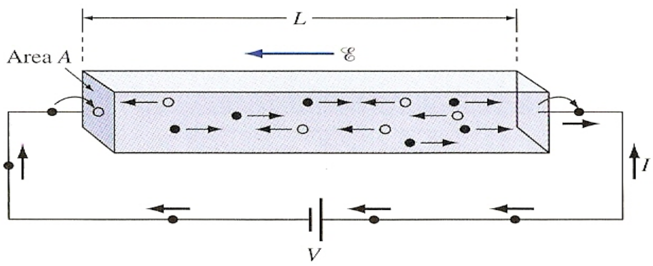
$$\boldsymbol{v}_n = -\mu_n \boldsymbol{E} \quad \text{and} \quad \boldsymbol{v}_p = \mu_n \boldsymbol{E}$$

$where:$
$\boldsymbol{v}_n = velocity\ of\ electrons\ (cm/s)$
$\boldsymbol{v}_p = velocit\ of\ hole\ (cm/s)$
$\mu_n = electron\ mobility,\ 1350\mathrm{cm}^2/V.s\ for\ intrinsic\ Si$
$\mu_p = hole\ mobility,\ 500\mathrm{cm}^2/V.s\ for\ intrinsic\ Si$

Drift Currents

- When an electric field is applies to a semiconductor, electron move in the opposite direction of holes which moves in the direction of the field
- The movement of electrons create the *electron drift current ($I_{n(drift)}$)* holes the *holes drift current($I_{p(drift)}$)*

Drift Currents



Total drift current $$I_{drift} = I_{n(drift)} + I_{p(drift)}$$

Prefer to use drift current density $$J_{drift} = \frac{I_{drift}}{A}$$

and $$J_{drift} = Q\,\mathbf{v}$$

where:

J_{drift} = drift current density

Q = charge density, charge per a unit volume (C/cm^3)

$\mathbf{v}$ = drift velocity (cm/s)

Conductivity,σ and Resistivity,ρ

- Conductivity in a material occurs when an electric field is applied to it which causes the charge carriers to move in a particular direction
- Current density is also defined: $J=\sigma E$

Also

$$J_{drift}=J_{n(drift)}+J_{p(drift)}$$

From drift velocity equation:

$$J_{drift}=(Q_p\mu_p+Q_n\mu_n)E$$

where

$Q_n=-qn$ and $Q_p=+qp$

therefore

$$J_{drift}=q(n\mu_n+p\mu_p)E$$

From above equation

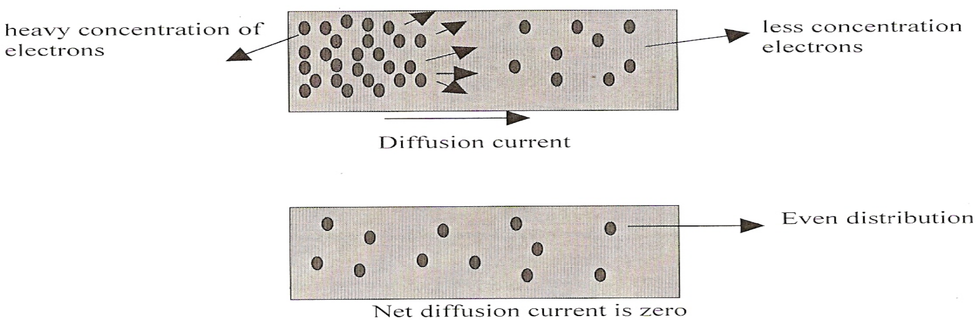
$$\sigma=q(n\mu_n+p\mu_p)$$

and

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

Diffusion Current

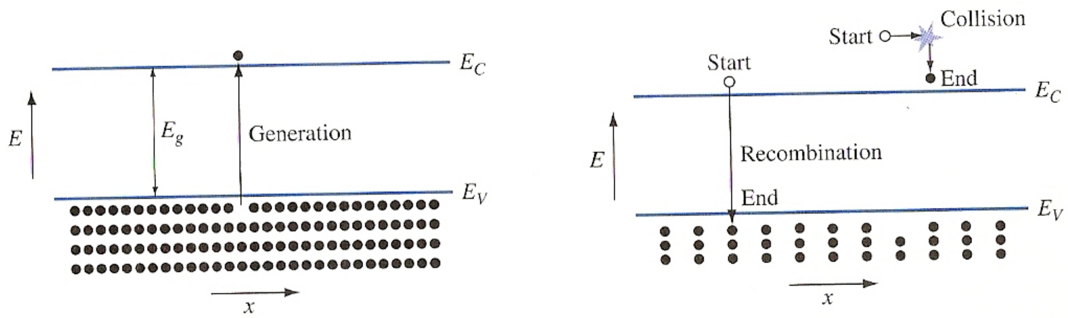
- Diffusion current is generated when charge carries move due to their concentration gradient without an electric field



Carrier Generation and Recombination

- Generation is the process of creating electron-hole pairs or exciting electrons from the valence band to the conduction band
- Recombination is the process by which electron fall from the conduction band to the valence band therefore destroying the electron hole pairs
- The length of time between generation and recombination is the *carrier lifetime*

Carrier Generation and Recombination



Carrier generation and recombination in semiconductors

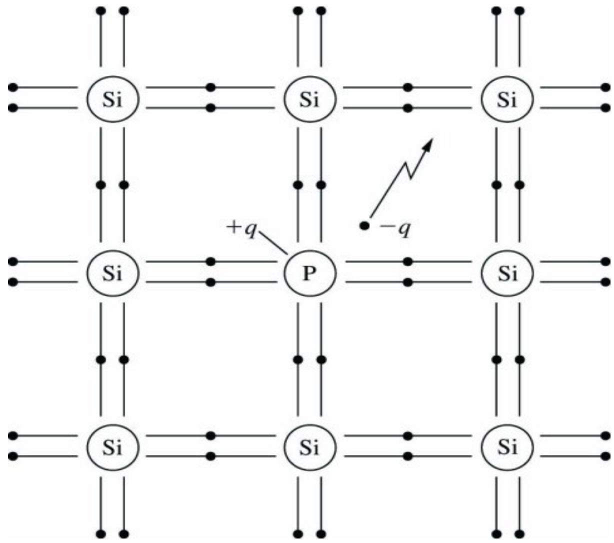
Impurities in Semiconductors

- Impurities are added from groups III or V to a semiconductor to increase the carrier concentration and hence change the resistivity of the semiconductor
- The process is termed doping which results in a ***doped*** or ***extrinsic*** semiconductor
- Impurities are either ***donor*** impurities or acceptor ***impurities***

Donor Impurities

- Donor impurities are from group 5 of the periodic table. e.g Phosphorous, P
- The have 5 valence electrons and therefore have a free electron after the covalent bonds are formed between the impurity (phosphorus) and the semiconductor (silicon)
- The majority charge carriers are electrons

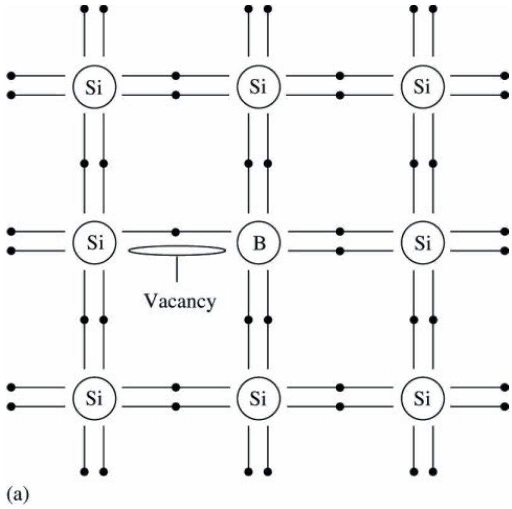
Donor Impurities



Acceptor Impurities

- Acceptor impurities are from group III of the periodic table. e.g Boron, B
- They have 3 valence electrons and there create a free space(hole) in the covalent bond
- Electron can easily jump into these holes causing the holes to move
- The majority charge carriers are holes

Acceptor Impurities



Acceptor Impurities