ECE 442

Power Semiconductor Devices and Integrated circuits

Spring, 2006

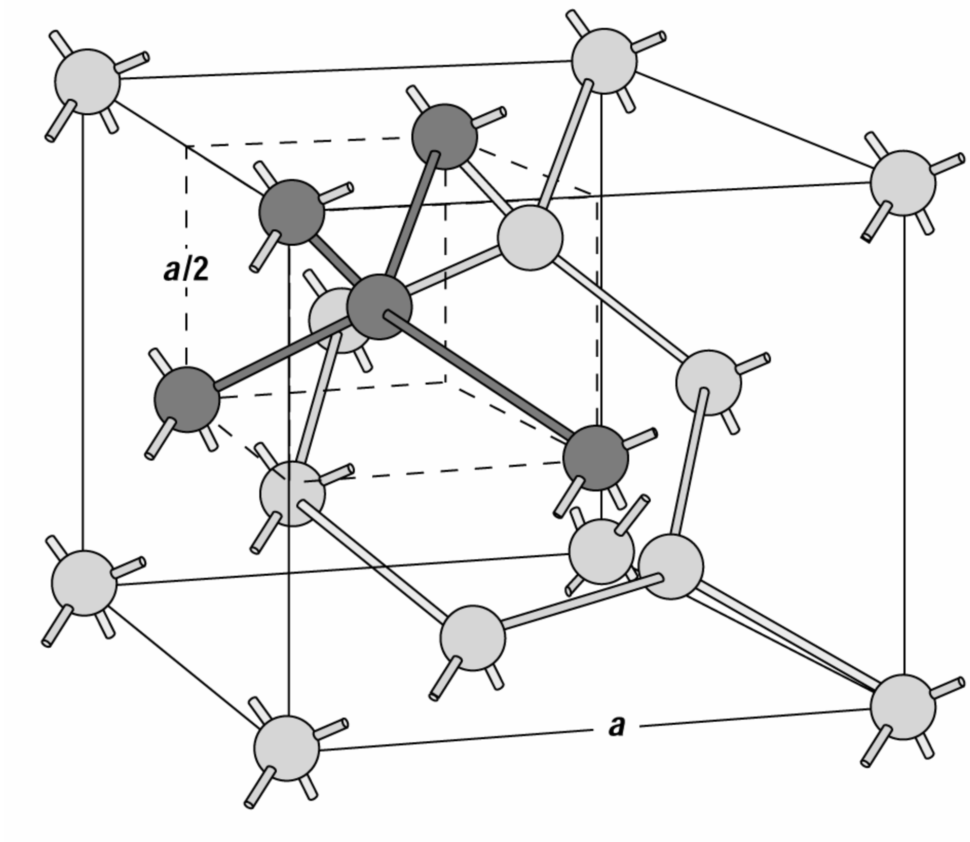
University of Illinois at Chicago

Lecture -2

Semiconductor physics – band structures and charge carriers

1. What are the types of charge carriers in a semiconductor?
2. P-type, N-type, dopants
3. What are ‘bands’?
4. What is Fermi energy level?
5. Density of states, carrier concentration in valence and conduction bands

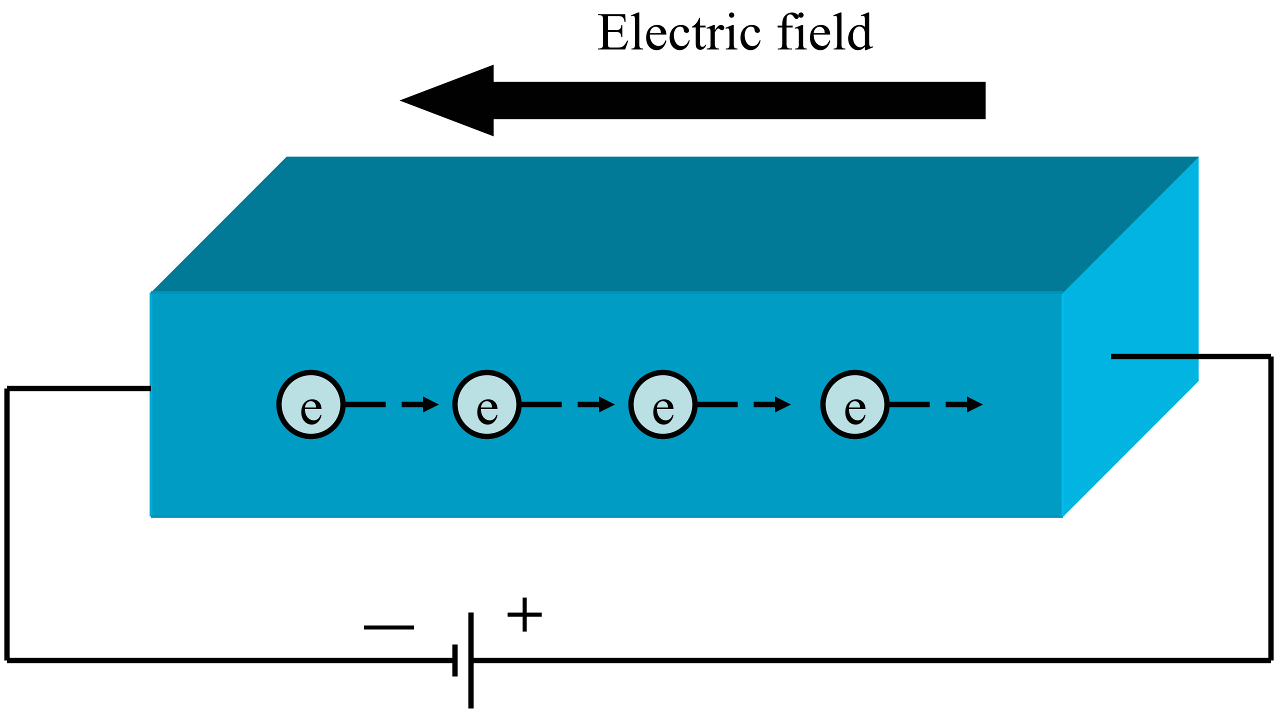
Crystal structure of silicon



- Silicon has a diamond crystal structure
- Atoms tetrahedrally bonded by valence sharing electrons
- Silicon atomic density 5×10^{22} cm^{-3}

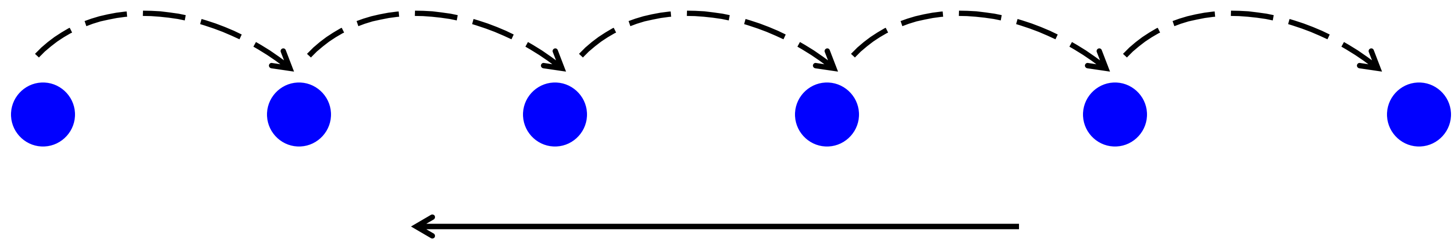
Electrons in semiconductor

- At 0 K, no bond is broken. Everyone is ‘satisfied’ and no free electron.
- At finite temperature, some bonds are broken and some free electrons are in the crystal lattice. They can move if an electric field is applied.

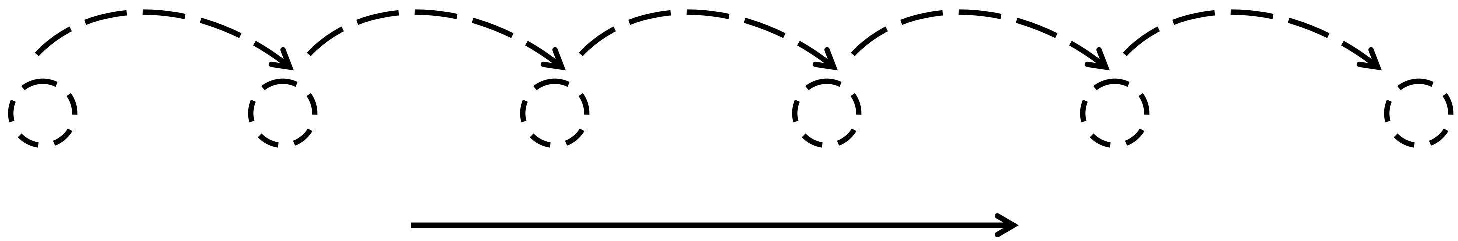


Holes in semiconductor

• An absence of electron is a ‘hole’. Electron has a charge of -1.6×10^{-19} C. Hole has a charge of $+1.6\times10^{-19}$ C. Hole has greater mass than electron.



Current direction by electrons

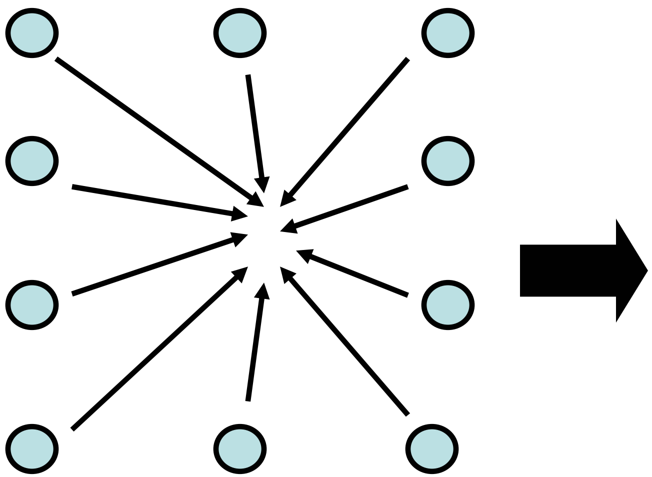


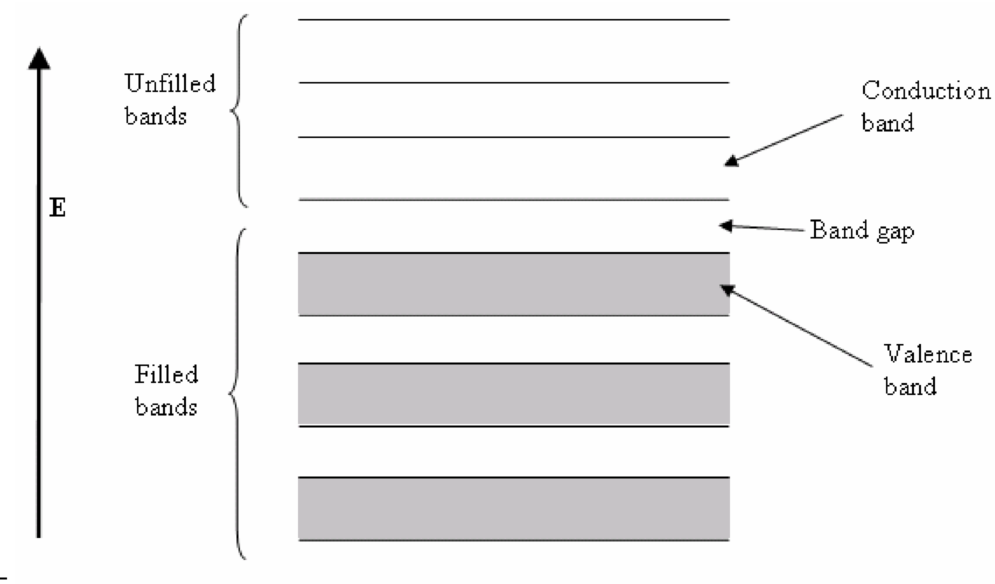
Current direction by holes

Donors and acceptors - doping

- ❑ Pure semiconductor is intrinsic – same number of electrons and holes. Overall charge-neutral.
- ❑ To make it slightly 'richer' in electrons we add some 'impurity'. They donate electron. They are called donors.
- ❑ To make it slightly 'richer' in holes we add some 'impurity'. They accept electron. They are called acceptors.
- ❑ Silicon is group-IV element is periodic table. It has 4 valence electrons.
- ❑ Donors (e.g. Arsenic, Phosphorus) are group-V electrons. They have 5 valence electrons.
- ❑ Acceptors (e.g. Boron, Aluminum) are group-III electrons. They have 3 valence electrons. They are short of one electron. So they accept!

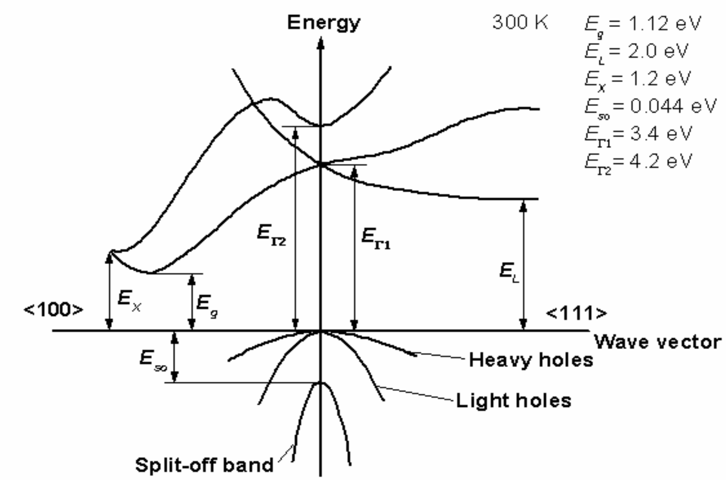
Bands



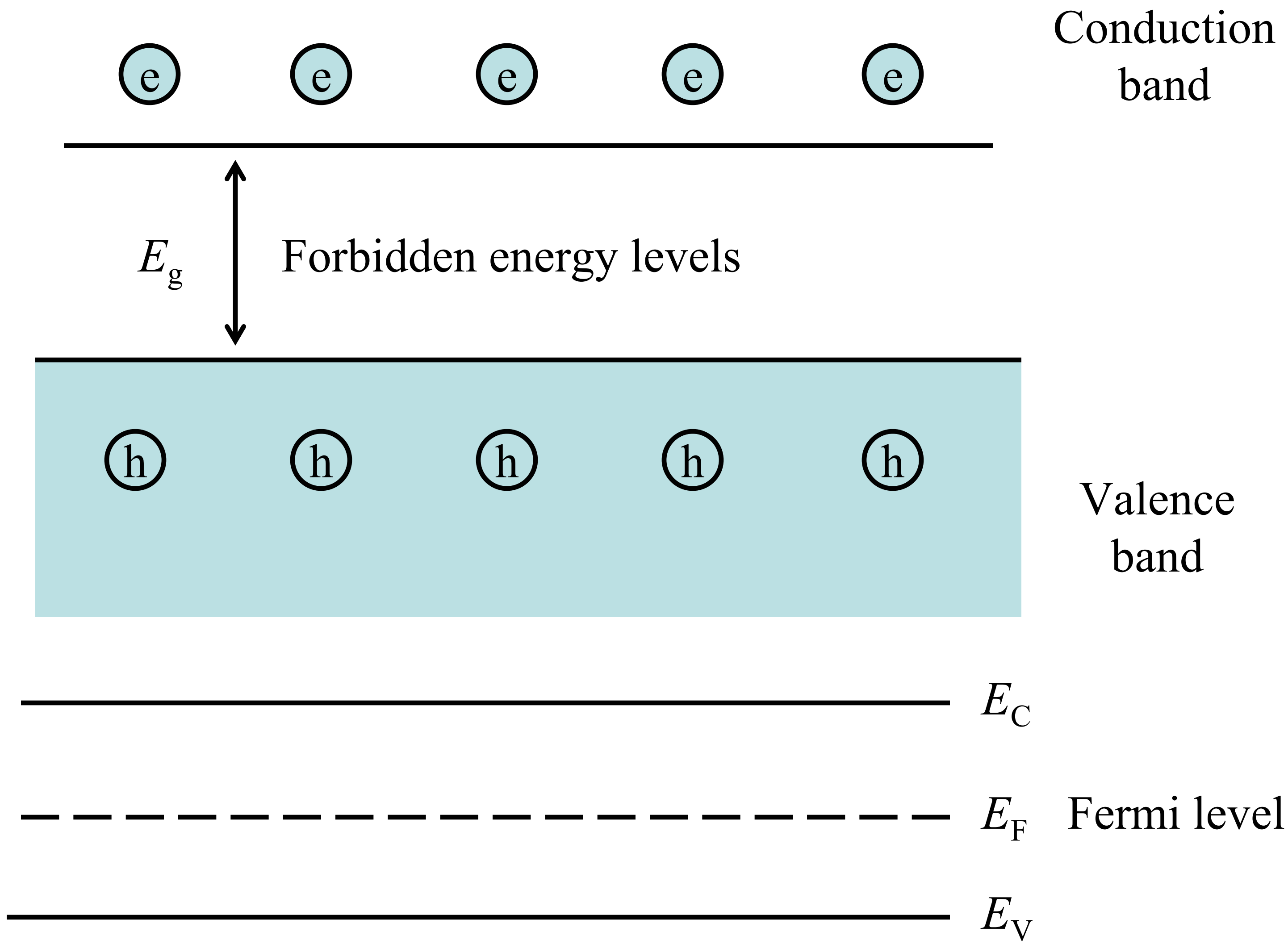


Multiple atoms coming together – form band structure

Actual band structures are quite complex. They depend on precise arrangement of atoms and are also anisotropic



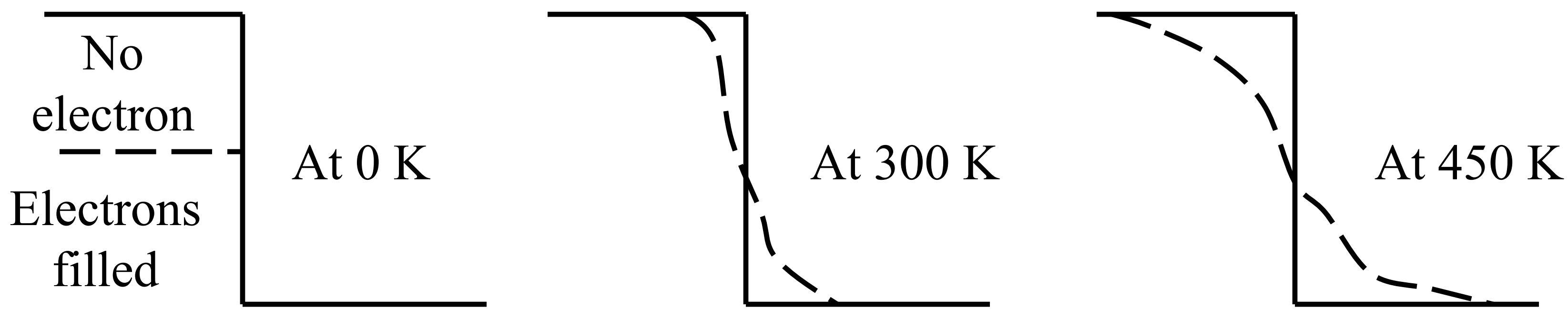
Simplified view of bands



Fermi energy/ Fermi level

The concept originated from Fermi-Dirac statistics which governs the distribution of particles in solids.

Fermi level denotes the energy level around which probability of finding an electron having some particular energy changes.



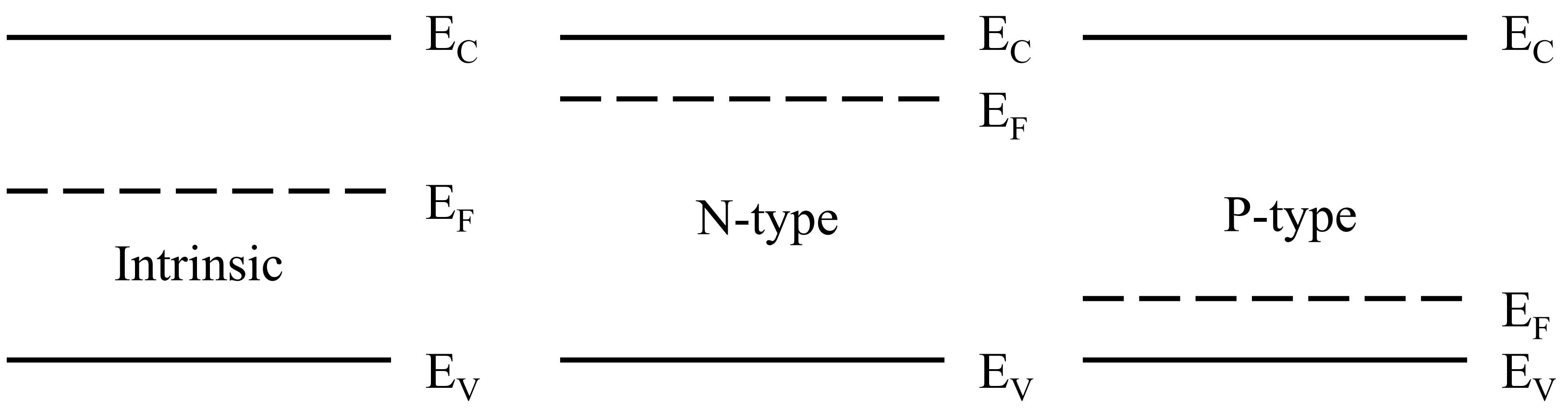
$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

Variation of Fermi level with doping

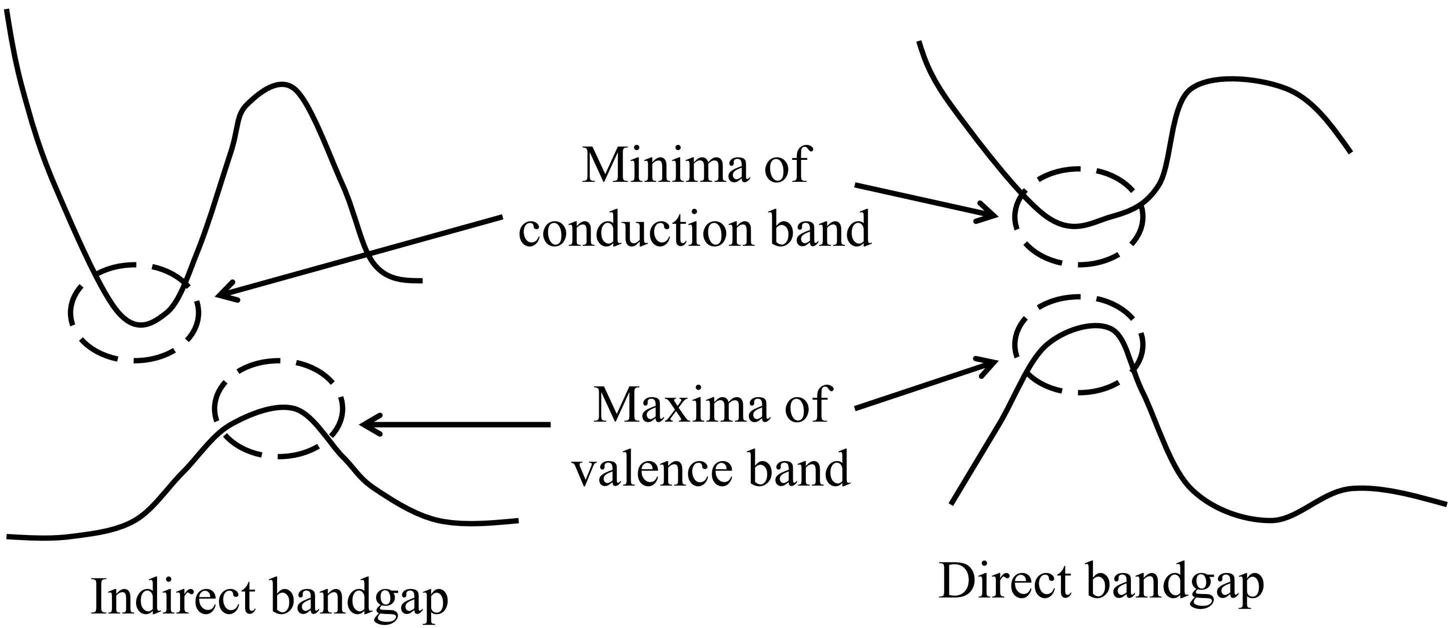
• For intrinsic semiconductor Fermi level is almost at the middle position between conduction band and valence band.

• For N-type semiconductor, there are more electrons than holes. Fermi level moves closer to the conduction band.

• For P-type semiconductor, there are more holes than electrons. Fermi level moves closer to the valence band.



Direct and indirect, wide and narrow bandgap



Silicon bandgap: 1.1 eV, indirect

Germanium bandgap: 0.62 eV, indirect

Gallium Arsenide bandgap: 1.42 eV, direct

Silicon carbide bandgap: 3.6 eV, indirect

Carrier density in bands

Intrinsic carrier density: $$n_i = 2\left(\frac{2\pi kT}{\hbar^2}\right)^{3/2}\left(m_n^* m_p^*\right)^{3/4} e^{-E_g/2kT}$$

Here *k* is Boltzmann constant, *T* is absolute temperature, *h* is Planck's constant, *m*'s are mass of electron and holes, E_g is bandgap energy

For silicon, at 300 K $n_i \sim 1.5\times10^{10}$ cm^{-3}

Electron density in conduction band: $$n_0 = n_i e^{(E_F - E_i)/kT}$$

Hole density in valence band: $$p_0 = n_i e^{(E_i - E_F)/kT}$$

At equilibrium: $$n_0 p_0 = n_i^2$$

Carrier densities in doped semiconductor

For N-type semiconductor, $n_\mathrm{n} = N_\mathrm{D}$

For P-type semiconductor, $p_\mathrm{p} = N_\mathrm{A}$

Electrons in N-type semiconductor are called ‘majority carriers’

Holes in P-type semiconductor are called ‘majority carriers’.

Electrons in P-type semiconductor are called ‘minority carriers’

Holes in N-type semiconductor are called ‘minority carriers’.

Majority carrier concentration = Doping density

Minority carrier density × Majority carrier density = (Intrinsic density)^2

Effective mass concept

- Mass of an electron in semiconductor (or in any solid in general) is not as same as the mass of an free electron!

- Quantum mechanics dictates that the mass of an electron in a solid depends on the internal atomic arrangement and crystal structure of the solid.

- We can say that the complexity of dealing with quantum mechanics is avoided by introducing the concept of '**effective mass**'.

$$m_n^* = \frac{1}{\hbar^2} \frac{1}{\left(\dfrac{d^2E}{dk^2}\right)}$$

E is energy and k is wave-vector

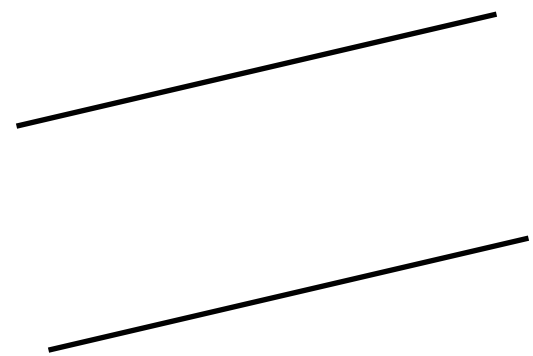
Band bending and continuity of Fermi level

Fermi level is **continuous** and **constant** across a semiconductor **at equilibrium**

Why? – Because Fermi level essentially denotes probability of finding electron, its variation means a different probability at different places. That means carriers would move which would constitute current.

But, valence and conduction bands get an upward or a downward 'push' under the influence of an external electric field

$$E = \frac{1}{q}\frac{dE_C}{dx} = \frac{1}{q}\frac{dE_V}{dx}$$



At equilibrium

Under electric field