Condensed Matter Physics

Impurity Levels in Doped Semiconductors

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Introduction

➢ In pure semiconductors (intrinsic semiconductors) the carrier concentration of both electrons and holes at normal temperatures is very low, and hence for an appreciable current density through the semiconductor, the applied electric field must be very large.

➢ The electrical conductivity of a semiconductor is very much dependent on purity and imperfections in the lattice.

➢ The electrical properties of solids are extremely sensitive to the presence and nature of even the tiniest amounts of impurity in the lattice.

➢ One way of increasing the conductivity of a semiconducting crystal is to add a controlled amount of certain impurities;

✓ The conductivity of silicon is increased thousand times by the addition of 10 parts per million (ppm) of boron. The conduction that occurs then is called impurity conduction.

✓ The impurity added are called *dopants*.

✓ When the impurity atoms are added into the semiconducting structure, the available quantum states are altered; one or more new energy levels may appear in band structure.

EXTRINSIC SEMICONDUCTOR

- In an extrinsic semiconducting material, the charge carriers originate from impurity atoms added to the original material is called impurity or extrinsic semiconductor.
- Extrinsic Semiconductor obtained by doping **trivalent** and **pentavalent** impurities in a **tetravalent** semiconductor.

DOPING

- The method of adding impurities to a pure semiconductor is known as **DOPING**, and the impurity added is called the doping agent (Eg- Pentavalent impurities: N, P, As, Sb and Trivalent impurities: B, Al, Ga, In).
- The addition of impurity would increases the number of free electrons and holes in a semiconductor and hence increases its conductivity.

❑ Types of semiconductors according to addition of impurities
  - ✓ n-type semiconductor
  - ✓ p-type semiconductor

- When small amounts of pentavalent impurity such as phosphorous are added during crystal formation, the impurity atoms lock into the crystal lattice.
- Consider a silicon crystal which is doped with a fifth column element such as P, As or Sb.
- Four of the five electrons in the outermost orbital of the phosphorus atom take part in the tetrahedral bonding with the four silicon neighbors.
- The *fifth electron* cannot take part in the discrete covalent bonding. It is *loosely* bound to the parent atom.

N – type semiconductor

- When pentavalent impurity is added to the intrinsic semiconductors, n-type semiconductors are formed.

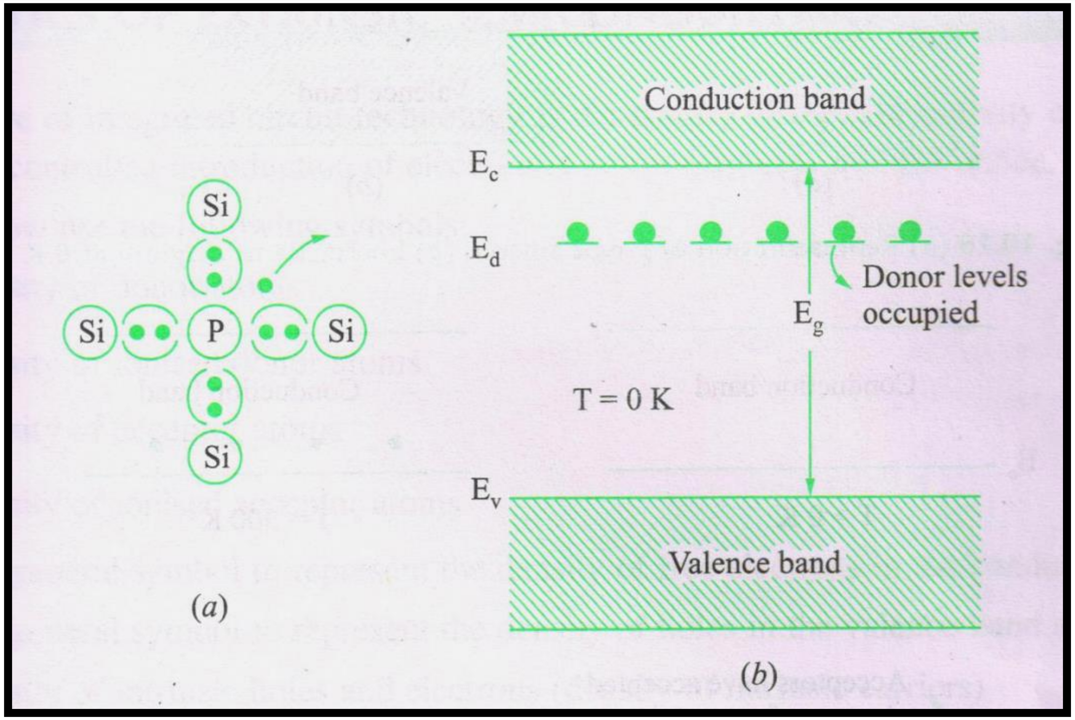
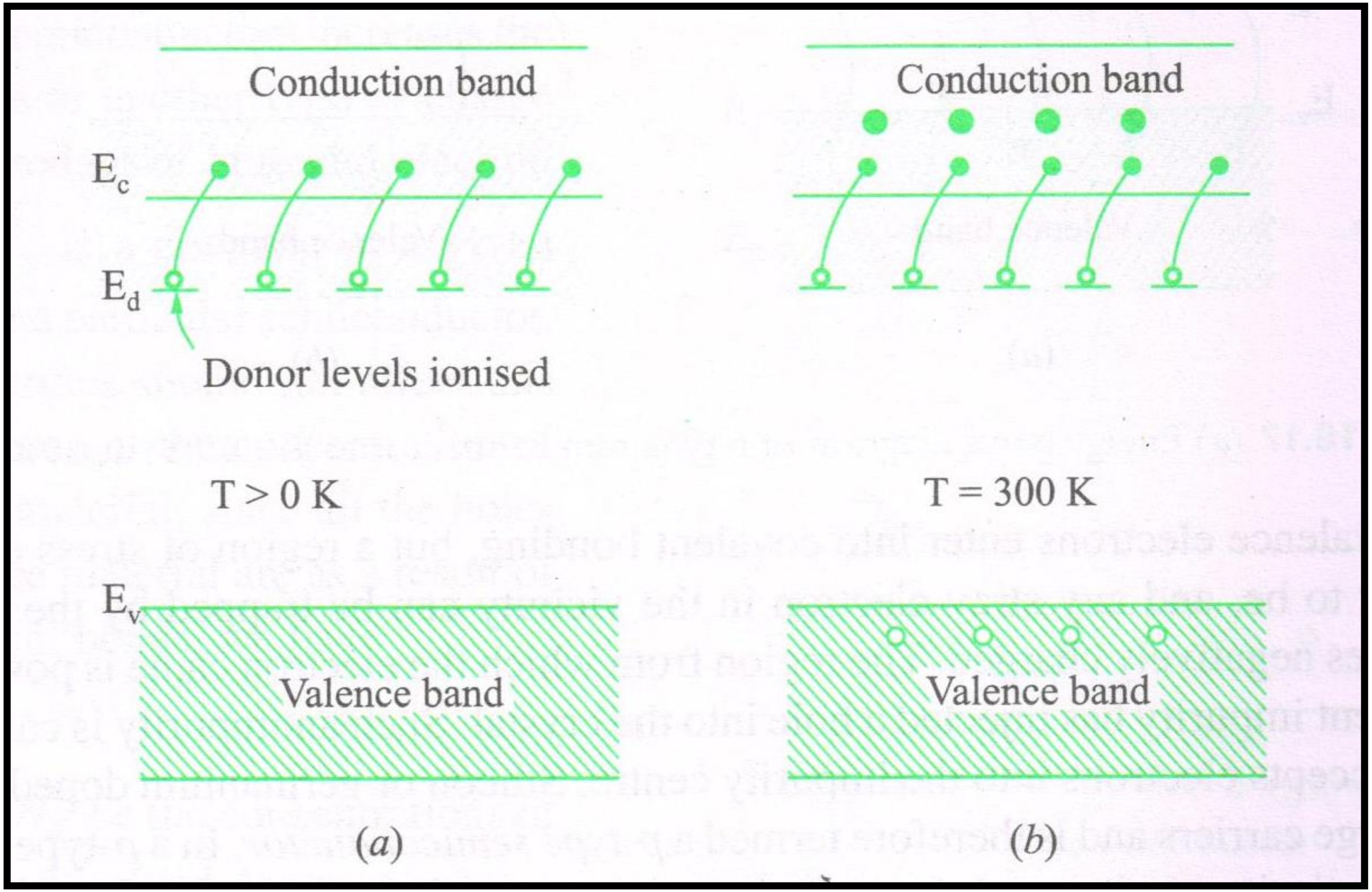


Fig: (a) Representation of n-type silicon, (b) Energy band diagram at 0 K

- At 0 K, the electronic system is in its lowest energy state, all the valence electron will be in the valence band and all the phosphorous atoms will be un-ionised.
- The energy levels of the donor atoms are very close to the conduction band.
- In the energy level diagram, the energy level of the fifth electron is called **donor level**. The donor level is so close to the bottom of the conduction band.
- Most of the donor level electrons are excited into the conduction band at room temperature and become majority charge carriers.

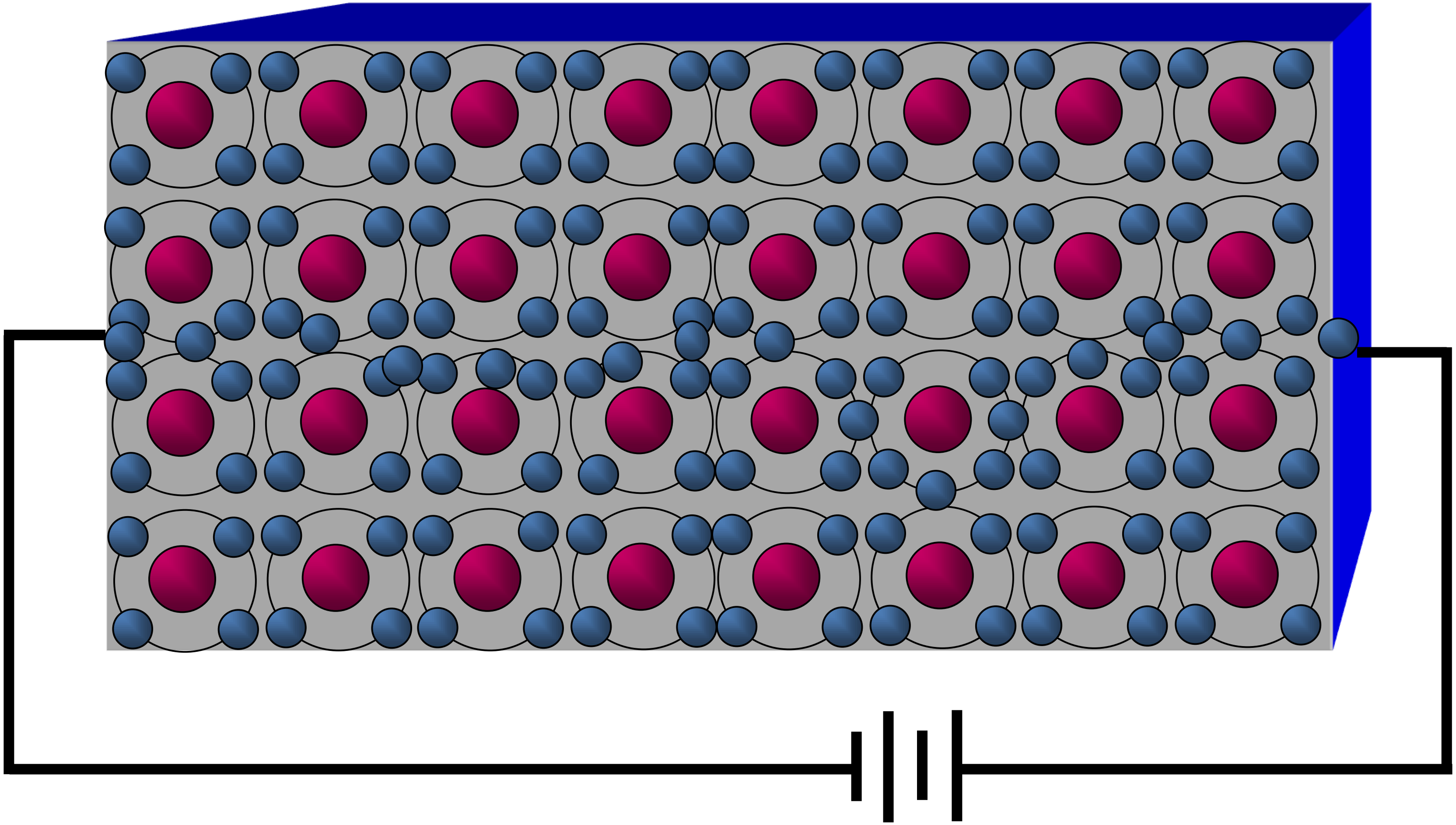


(a) (b)

Fig: (a) Energy band diagram of n-type semiconductor at T>0, (b) At T=300K

- If the thermal energy is sufficiently high, in addition to the ionization of donor impurity atoms, breaking of covalent bonds may also occur thereby giving rise to generation of electron hole pair.
- Thus electrons are more in number than holes and hence electrons are majority carriers and holes are minority carriers.

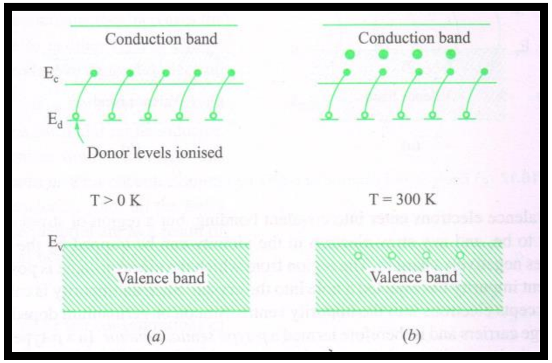
Si crystal doped with a pentavalent (Group V atom) impurity.



The almost free electrons in n type silicon support the flow of current.

Fermi energy

The Fermi energy for n – type semiconductor is given by



$$E_F = \frac{(E_c + E_d)}{2} + \frac{kT}{2}\ln\left[\frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}}\right]$$

At 0 K, $$E_F = \frac{(E_c + E_d)}{2}$$

Variation of Fermi level with temperature

The Fermi energy is given by,

$$E_F = \left(\frac{E_d + E_c}{2}\right) + \frac{kT}{2}\ln \frac{N_d}{2\left[\frac{2\pi m_e * kT}{h^2}\right]^{3/2}}$$

Let $$2\left[\frac{2\pi m_e * kT}{h^2}\right]^{3/2} = N_x$$

$$= \left(\frac{E_d + E_c}{2}\right) - \frac{kT}{2} ln\left(\frac{N_d}{N_x}\right)^{-1}$$

P – type semiconductor

- ➢ When trivalent impurity is added to the intrinsic semiconductors, p-type semiconductors are formed.

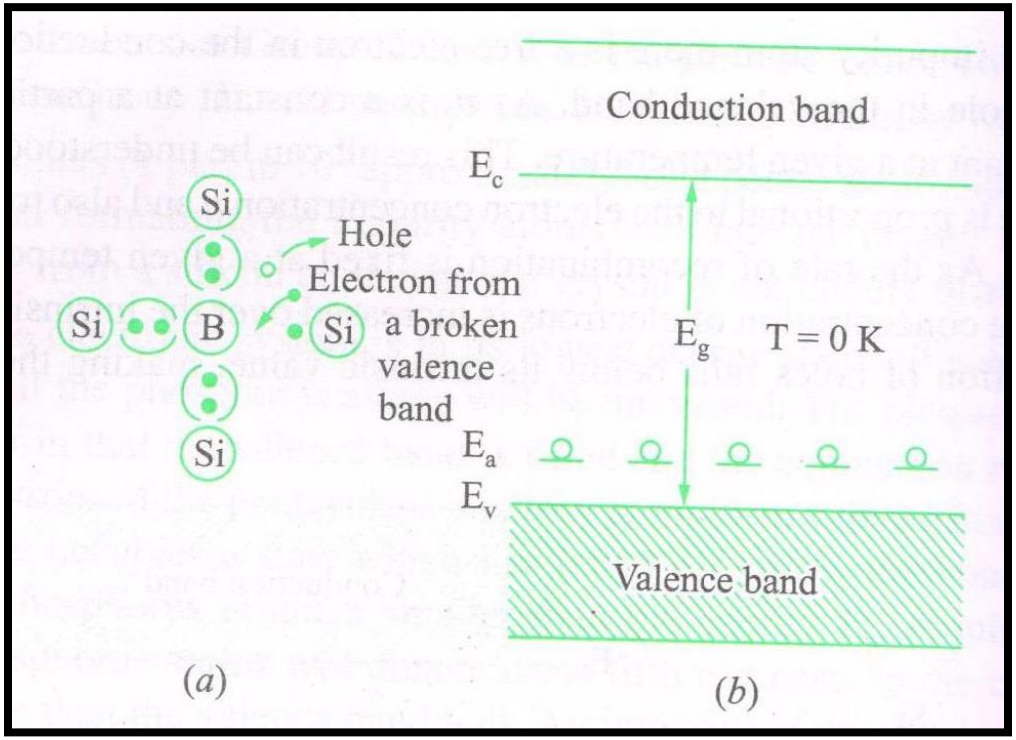


Fig: (a) Representation of p-type silicon, (b) Energy band diagram at 0 K

- ➢ B has three electrons in the outer orbital. While substituting for silicon in the crystal, it *needs an extra- electron* to complete the tetrahedral arrangement of bonds around it.
- ➢ The extra electron can come only from one of the neighbouring silicon atoms, thereby creating a vacant electron site (hole) on the silicon.
- ➢ The boron atom with the extra electron becomes a negative charge and the hole with a positive charge can be considered to resolve around the boron atom.

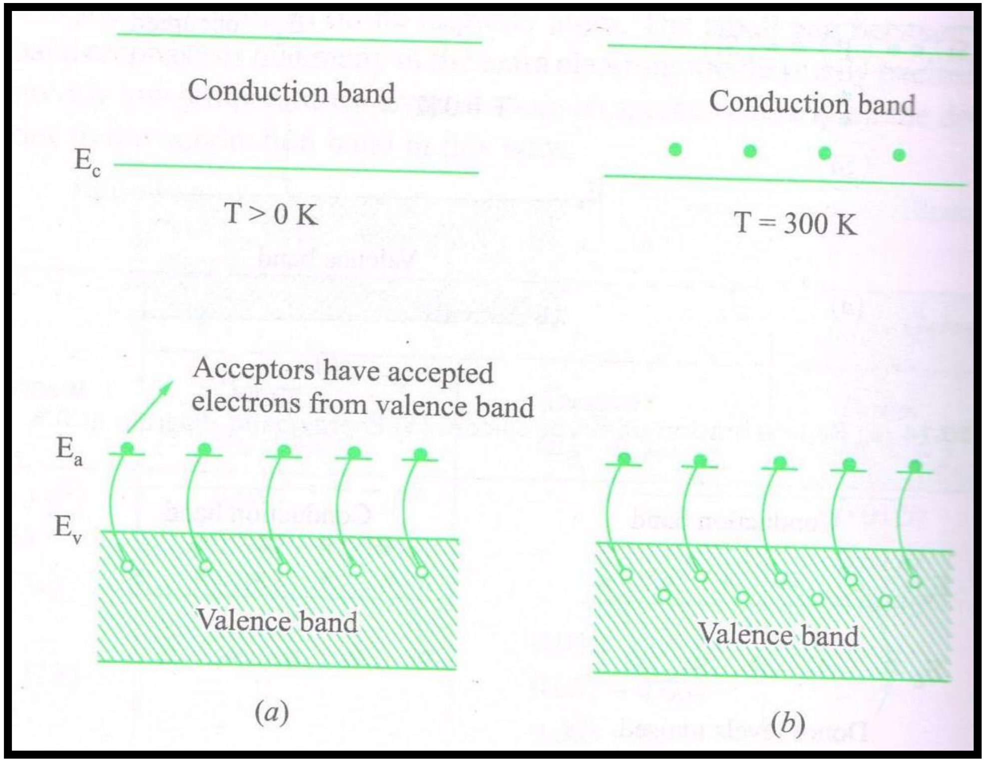
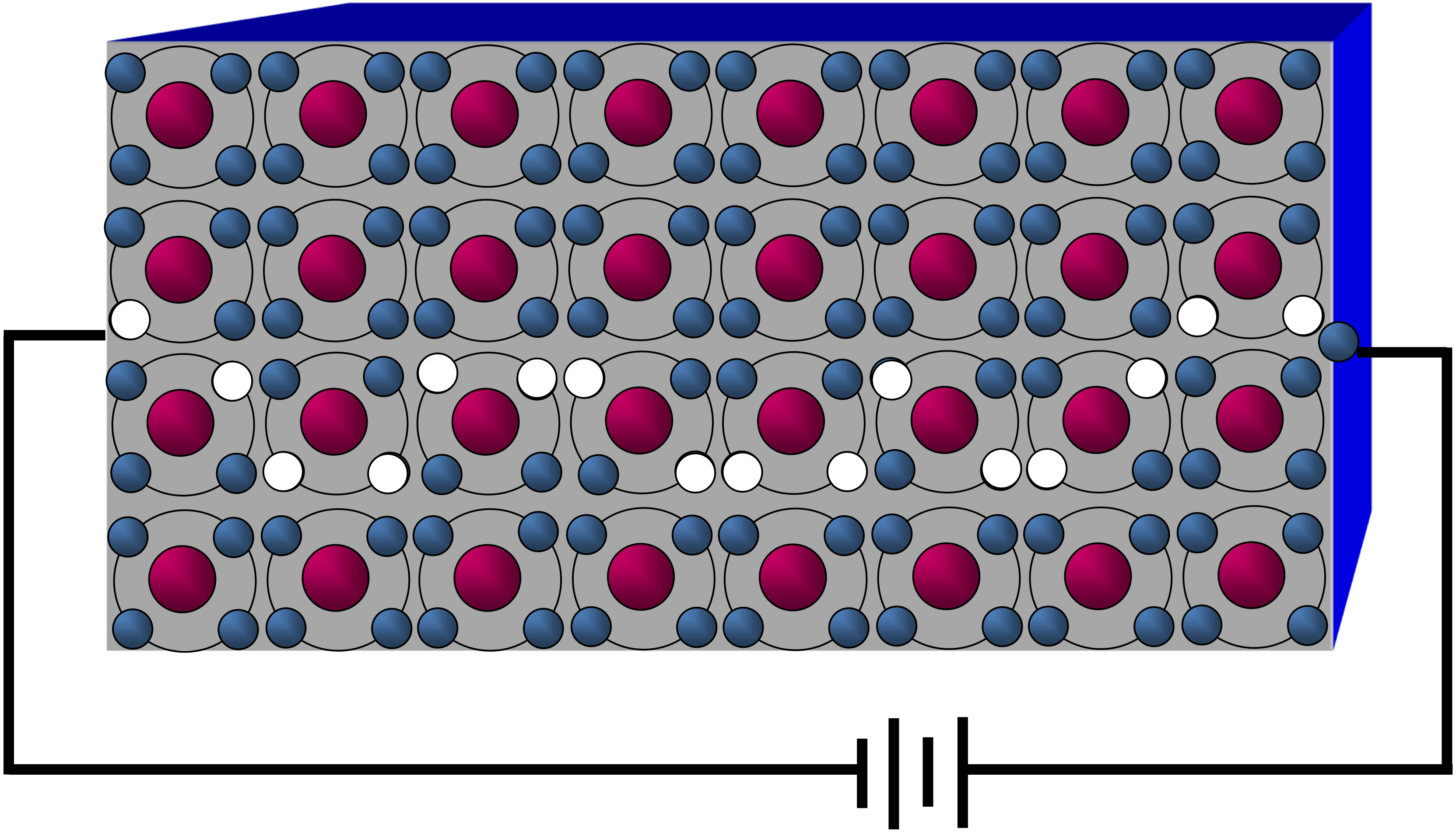


Fig: (a) Energy band diagram of p-type semiconductor at T>0, (b) At T=300K

- Since the trivalent impurity accepts an electron, the energy level of this impurity atom is called **acceptor level**. This acceptor level lies just above the valence bond.
- Even at relatively low temperatures, these acceptor atoms get ionized taking electrons from valence bond and thus giving to holes in the valence bond for conduction.
- Due to ionization of acceptor atoms, only holes and no electrons are created.
- If the temperature is sufficiently high, in addition to the above process, electron-hole pairs are generated due to the breaking of covalent bonds.
- Thus holes are more in number than electrons and hence holes are majority carriers and electrons are minority carriers

This crystal has been doped with a trivalent impurity.

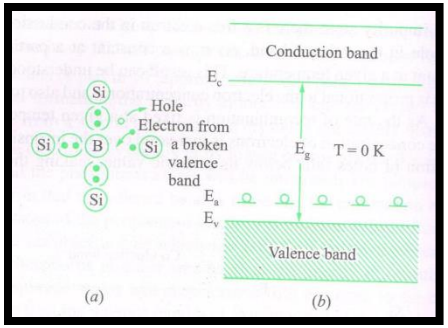


The holes in p type silicon contribute to the current.

Note that the hole current direction is **opposite** to electron current so the electrical current is in the same direction

Fermi Energy

The Fermi energy for p – type semiconductor is given by



$$E_F = \left(\frac{E_v + E_a}{2}\right) - \frac{kT}{2} ln \left[\frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}} \right]$$

At 0 K, $E_F = \frac{E_v + E_a}{kT}$

At 0K, Fermi level is exactly at the middle of the acceptor level on the top of the valence band.

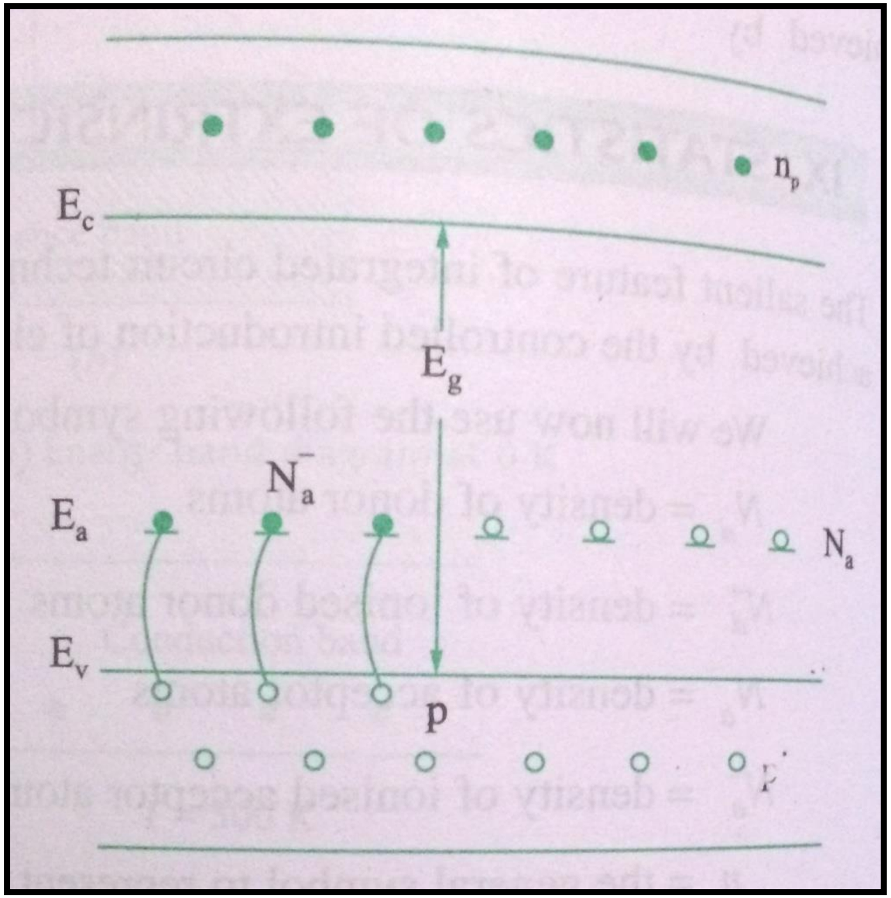
Variation of Fermi level with temperature

The Fermi energy is given by,

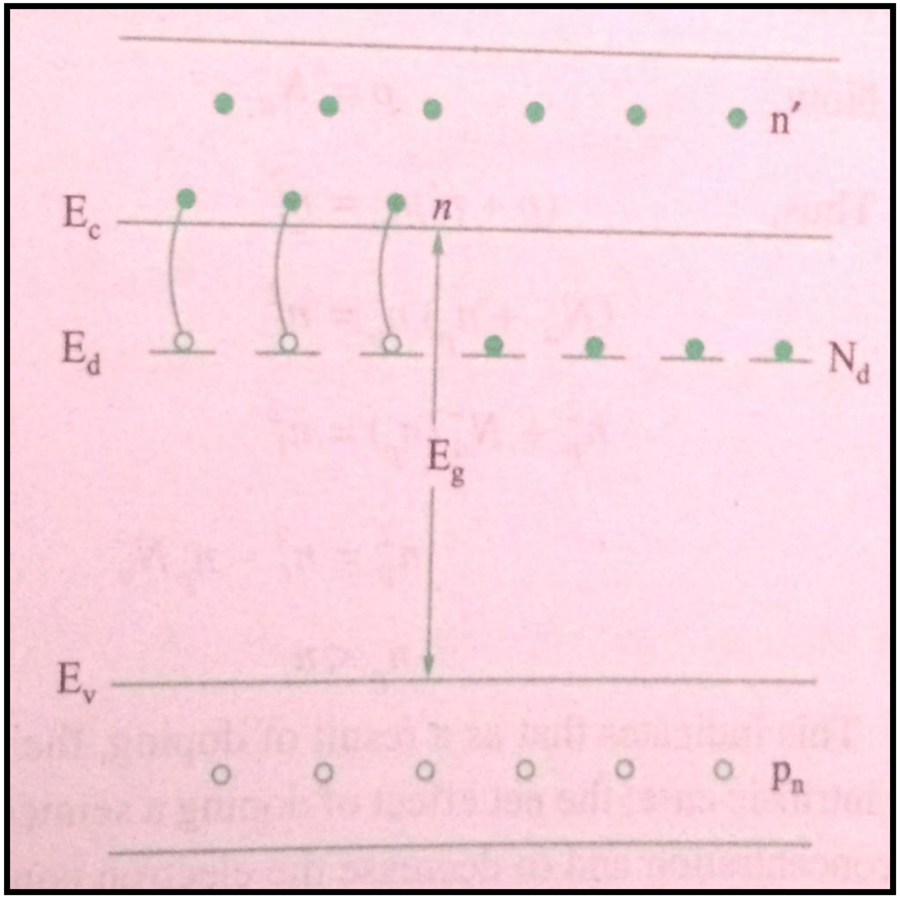
$$E_F = \left(\frac{E_v + E_a}{2}\right) - \frac{kT}{2} ln \left(\frac{N_a}{2\left(\frac{2\pi m_h{}^* \, kT}{h^2}\right)^{3/2}} \right) = \left(\frac{E_v + E_a}{2}\right) - \frac{kT}{2} ln \left(\frac{N_a}{N_y}\right)$$

where $N_y = 2\left(\frac{2\pi m_h{}^* kT}{h^2}\right)^{3/2}$ and therefore $E_F = \left(\frac{E_v + E_a}{2}\right) + \frac{kT}{2} ln \left(\frac{N_a}{N_y}\right)$

- From the above equation, it is seen that E_F increases slightly as the temperature increases.
- As the temperature increases, more and more acceptor atoms are ionised.



Energy Level diagram of p-type semiconductor



Energy Level diagram of n-type semiconductor