Semiconductors

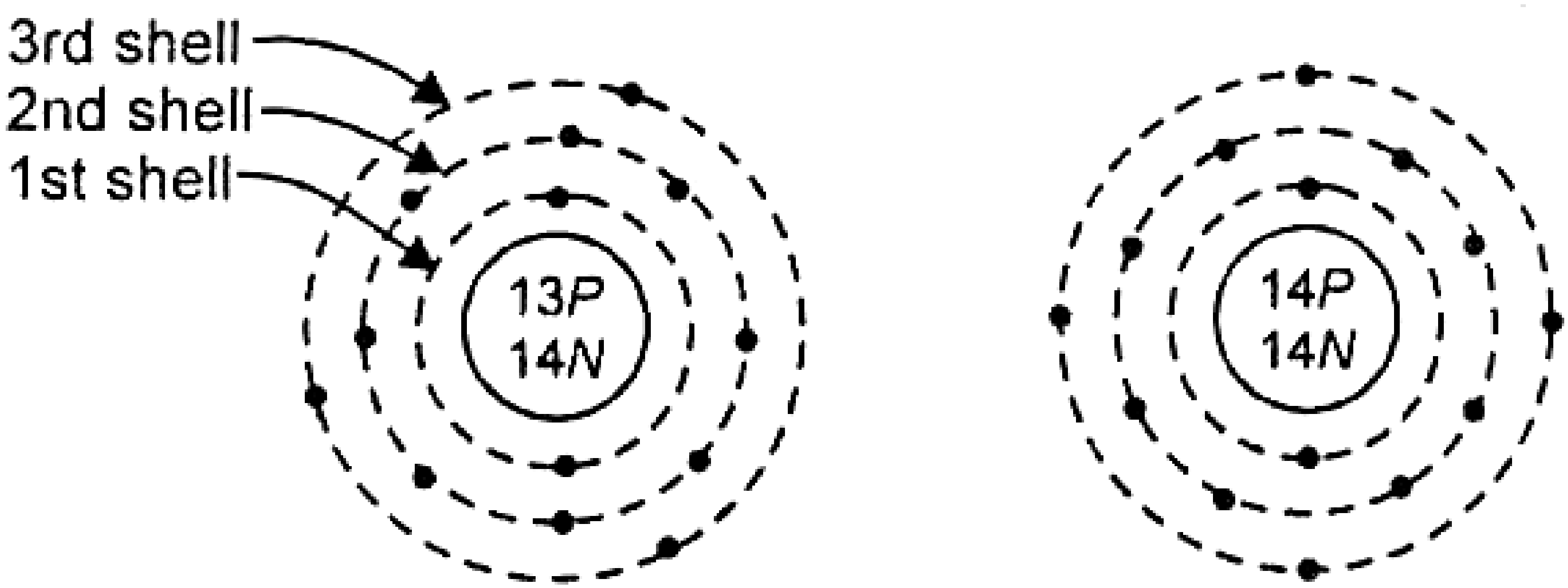
- Conductivity is in between that of conductors and insulators.
- Concentration of free electrons is moderate and is in between that of conductors and insulators.
- Germanium and Silicon, which has tetravalent atoms are the two most important semiconductors used in electronic devices.

- Width of the forbidden gap is relatively small ~ 1 eV.

  At 0^0 K : E_g for Ge ~ 0.785 eV

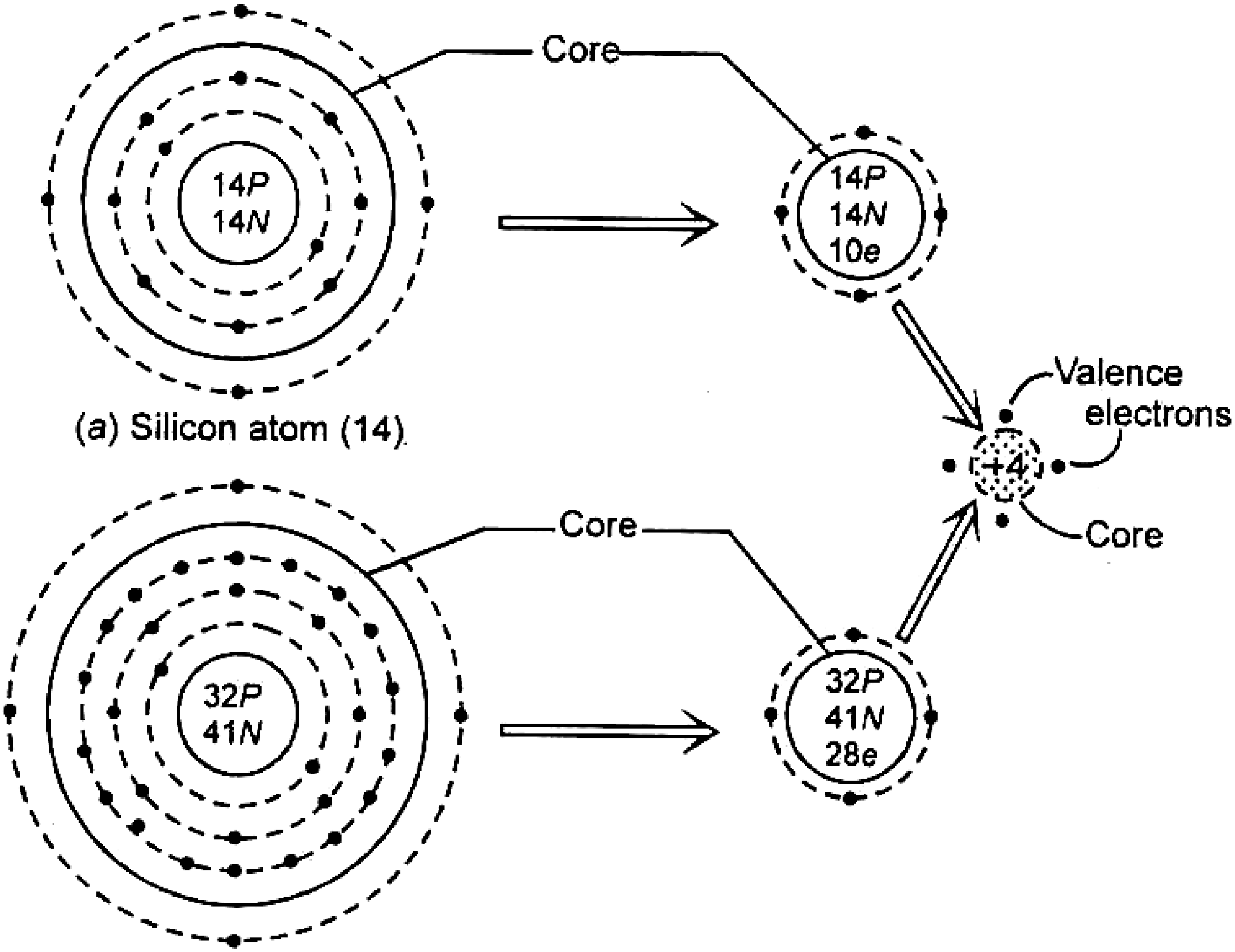
  E_g for Si ~ 1.21 eV
- Band gap energy in a crystal is a function of interatomic spacing and hence depends somewhat on temperature.
- Has negative temperature coefficient of resistance, i.e., resistance decreases with rise ion temperature.

Atomic Structure



(a) Aluminium atom (13)   (b) Silicon atom (14)

Simplified Representation of Atoms

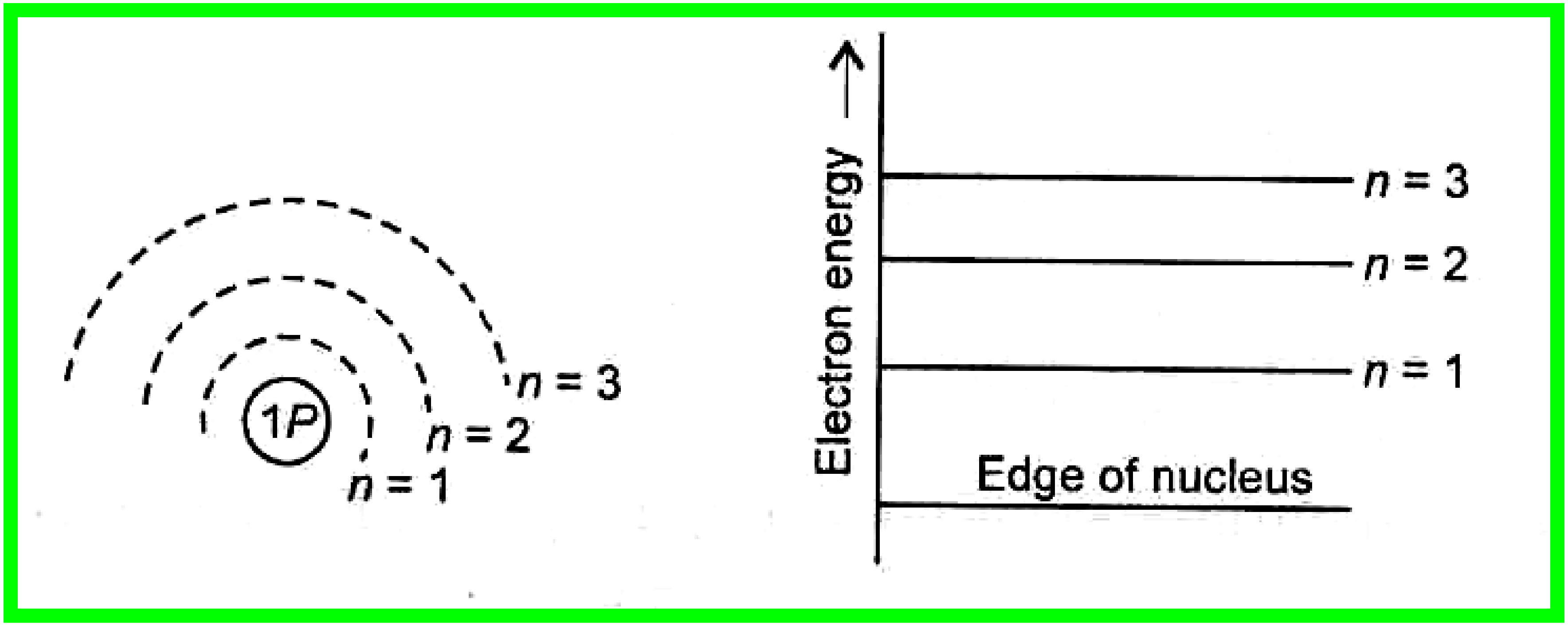


(a) Silicon atom (14)

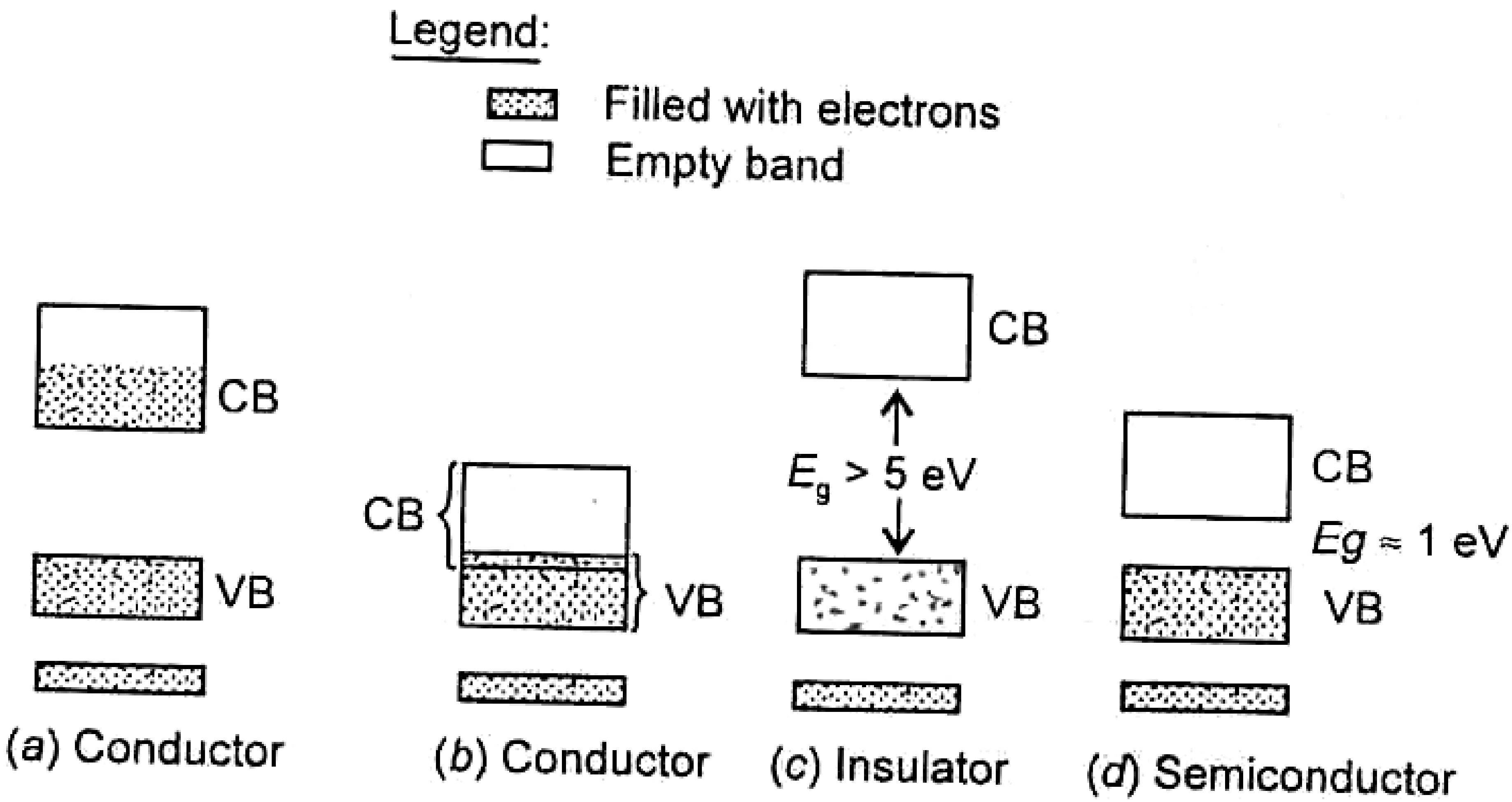
(b) Germanium atom (32)

Permissible Energy Levels

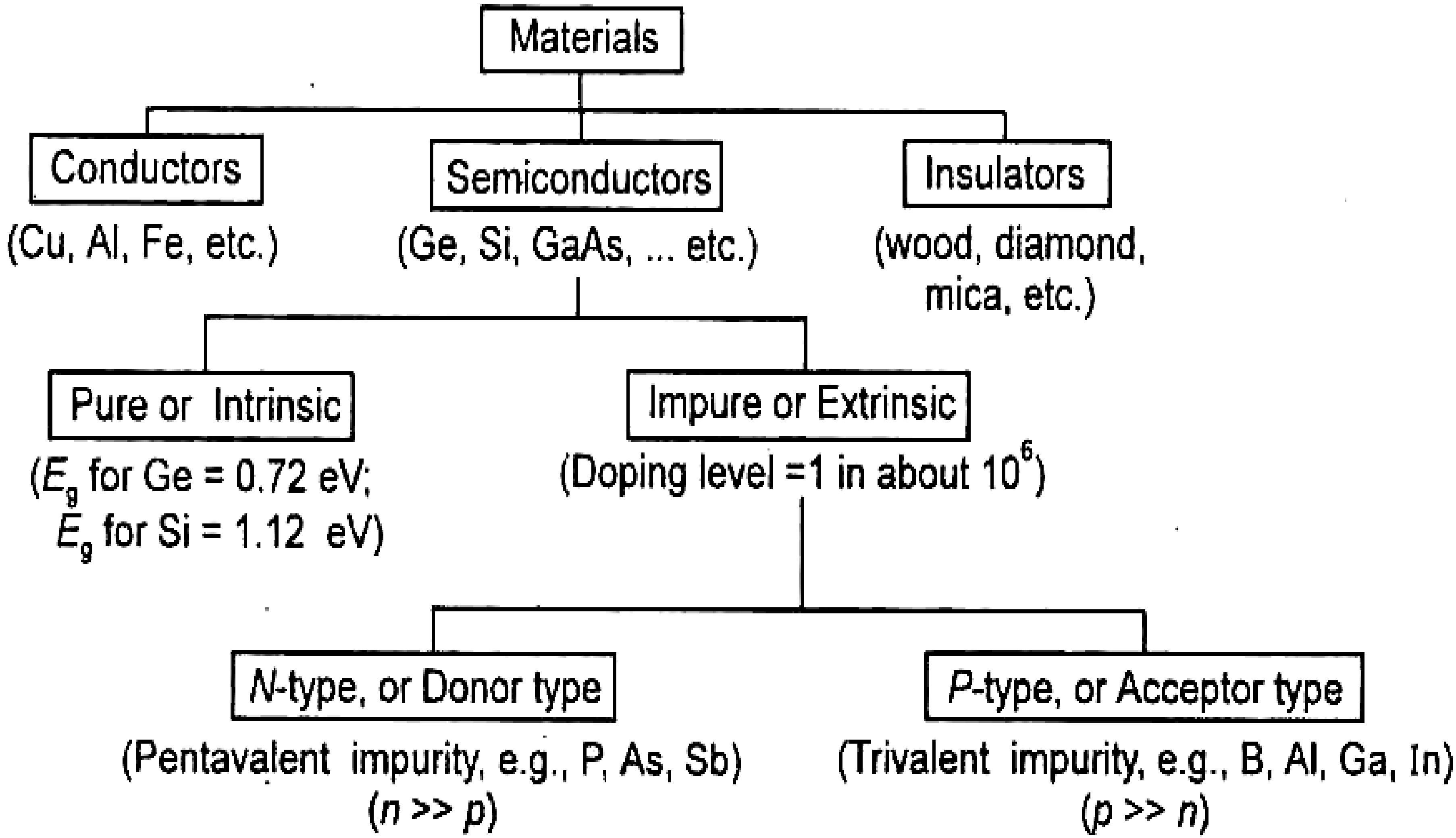
(for an isolated hydrogen atom)



Energy Bands



Semiconductors



Types of Semiconductors

Intrinsic Semiconductor

The semiconductor formed by pure tetravalent Silicon or Germanium is known as the Intrinsic Semi-conductor.

For Intrinsic: n = p = ni

Extrinsic Semiconductor

The semiconductor formed by deliberate doping of trivalent or pentavalent impurities in tetravalent Silicon or Germanium is known as Extrinsic Semiconductor

Intrinsic Semiconductors

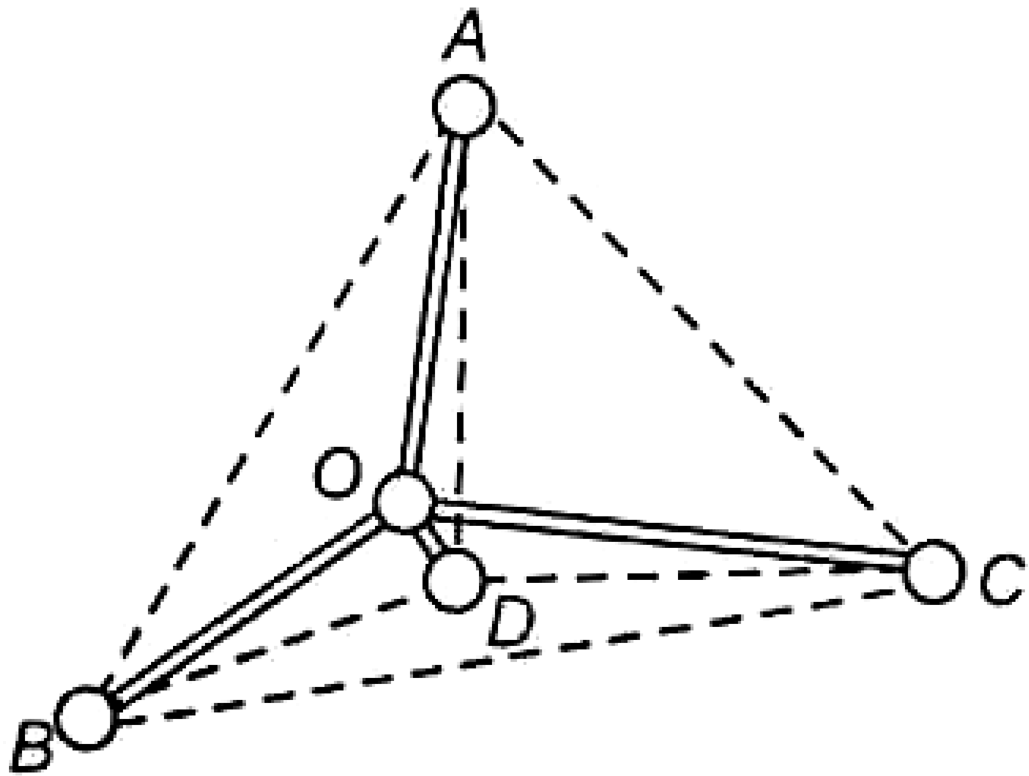
- Electrons and Holes in Intrinsic Semiconductors
- Covalent Bond in Intrinsic Semiconductor Crystal
- Generation of Electron-Hole Pair
- Effective Mass

Crystal Structure of Semiconductors

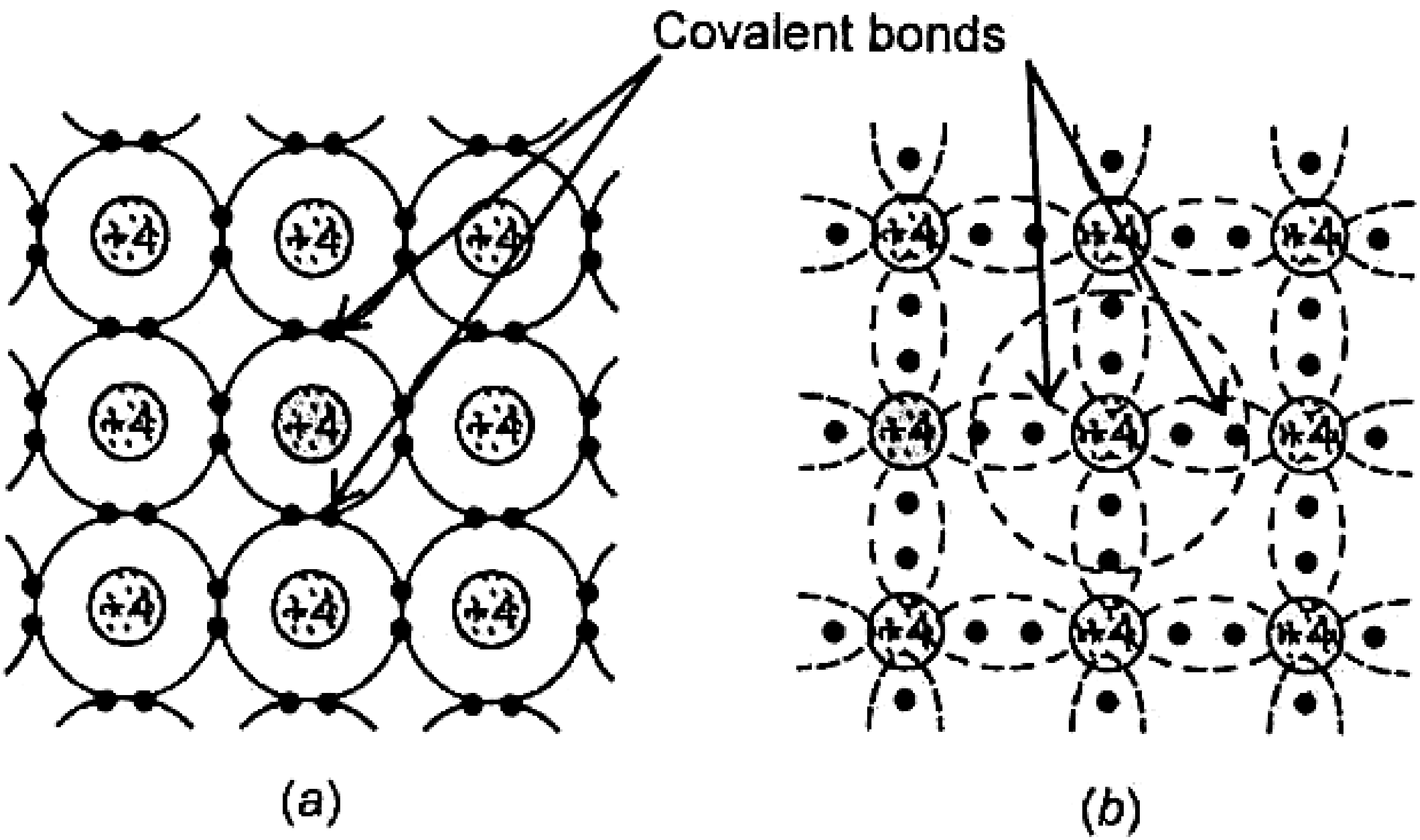
- The valence electrons in semiconductors are not free to wander about as in metal, rather are trapped in a bond between two adjacent atoms.

- The crystal structure of tetravalent Germanium or Silicon crystal consists of regular repetition of a unit cell in three dimensions having the form of a tetrahedron with an atom at each vertex.

Tetrahedron formed.



Crystalline structure
(Two dimensional representation)

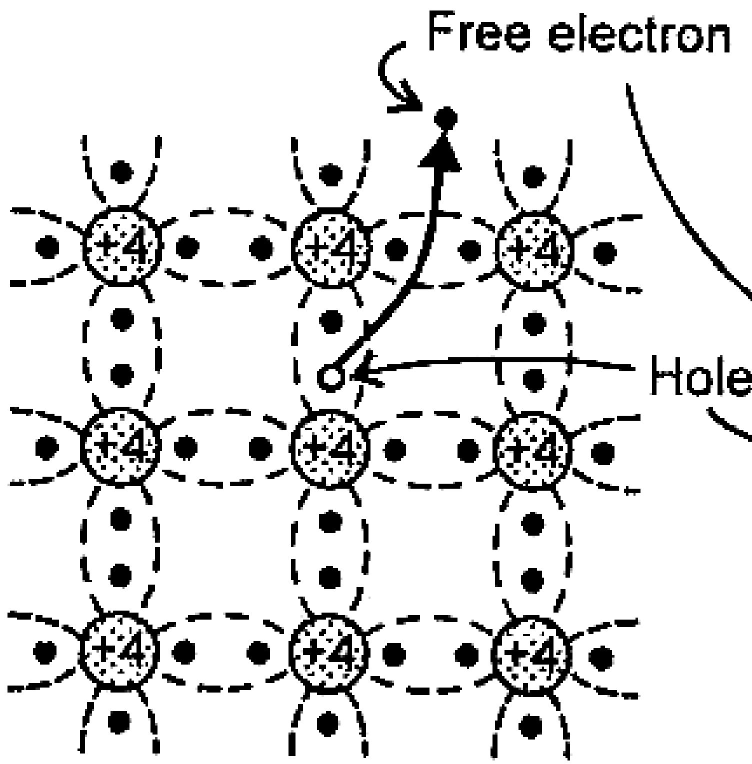


Generation of Electron-Hole Pair

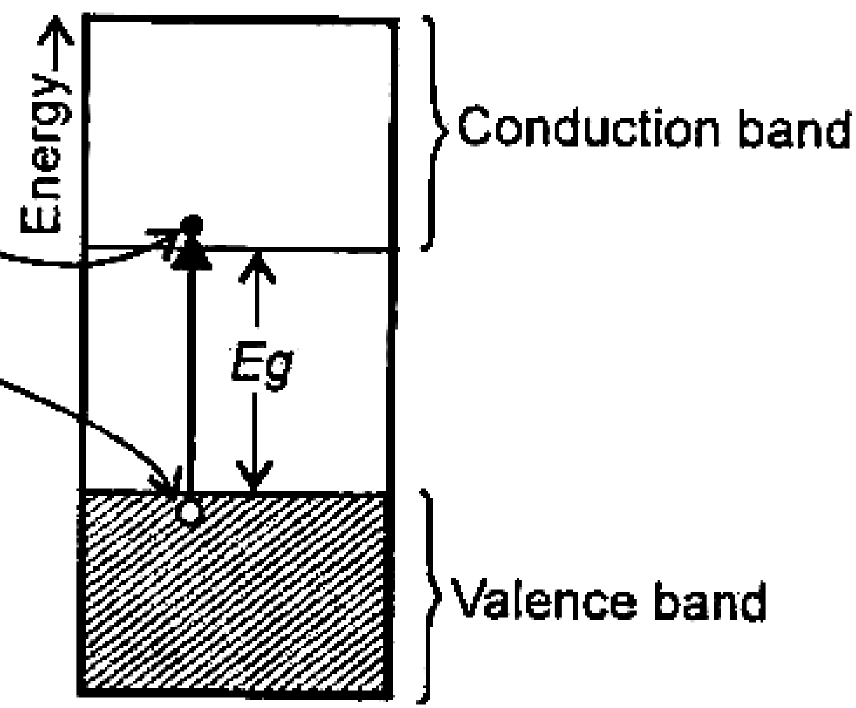
- At very low temperature (0^0K) the crystal behaves like a perfect insulator, since no free carriers of electricity are available.

- At room temperature some of the covalent bonds will be broken because of the thermal energy supplied to the crystal.

- An electron is dislodged and is free to move in a random fashion throughout the crystal, just like electrons in a metal. The vacant place is a hole.



(*a*) Crystal structure



(*b*) Energy-band diagram

- The energy required to break such a covalent bond is about 0.72 eV for Ge and 1.12 eV for Si at room temperature (300 K).
- When an electron breaks away, only 3 electrons are left around a core with +4 charge.
- This vacancy is called a *hole.*
- Hole is a vacancy in a covalent bond, which has +1 unit charge associated with it.

- In an intrinsic semiconductor the number of holes is equal to the number of free electrons, i.e.,

$$n = p = n_i$$

where n and p are the electron and hole concentration respectively and n_i is called the intrinsic carrier concentration.

Contribution of holes to conductivity

- The importance of holes is that they serve as the carriers of electricity, comparable in effectiveness with free electron.

- When a bond is incomplete (a hole exists), it is relatively easy for a valence electron in a neighboring atom to leave its covalent bond to fill this hole.

- Hence the hole effectively moves in the direction opposite to that of the electrons.

Hole as a Particle

- **Hole is just a vacancy, having a positive charge.**
- **For convenience, we treat hole as a particle.**
- **Both the electron and hole have same amount of charge ($e = 1.6 \times 10^{-19}$ C).**
- **We associate with a hole, a mass called effective mass, though it is meaningless.**
- **It is possible to treat the hole and electron as imaginary charged particle with effective positive masses m_p and m_n, respectively.**
- **The effective mass of a hole is more than that of an electron. That is,**

$$m_p > m_n$$

Because, the hole moves slower than an electron, when same external field is applied.

Recombination of Electrons and Holes

- Recombination is a process in which the free electrons in the conduction band jumps into the valence band to combine with holes.

- In the process of recombination the electron-hole pair is destroyed.

- The rate of recombination is approximately proportional to the product of electron concentration and hole concentration.

- In the recombination process the minimum energy released in the form of electromagnetic radiation is equal to the band gap.

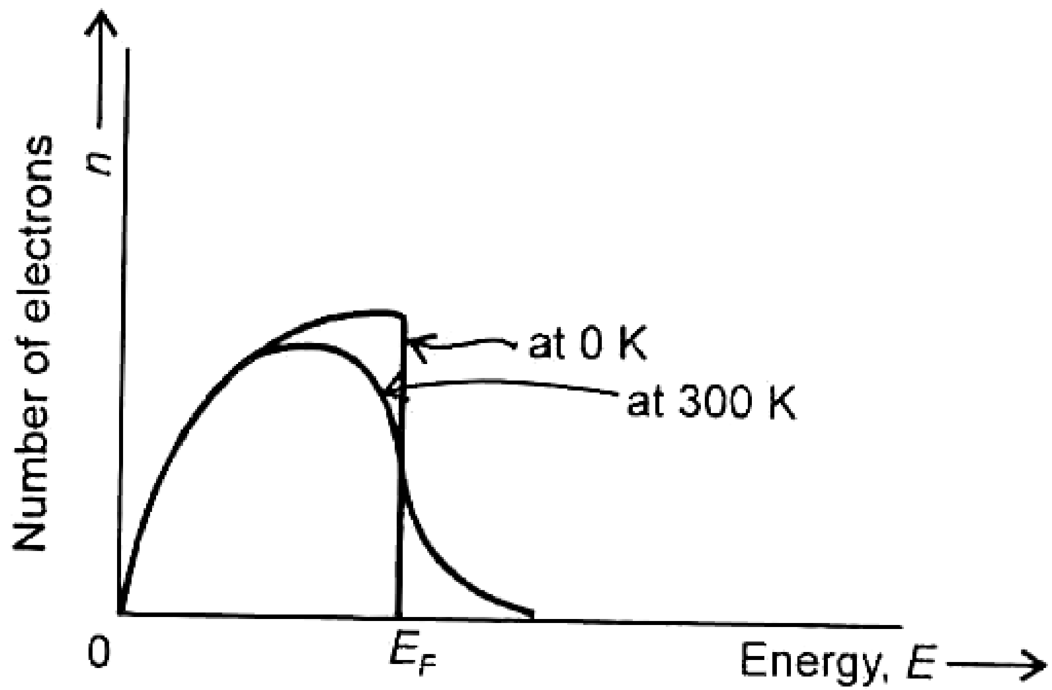
- **While some electron hole pair is lost by recombination, new pairs are generated due to thermal excitation.**
- **For pure semiconductors at constant temperature the rate of recombination and the rate of generation of the electron-hole pairs are equal so that the electron and hole concentrations remain constant at their thermal equilibrium value.**

$$r = g$$

- **If the temperature increases, the thermal equilibrium value of the electron and the hole concentration also increases.**

Fermi Energy Level

(In a Conductor)

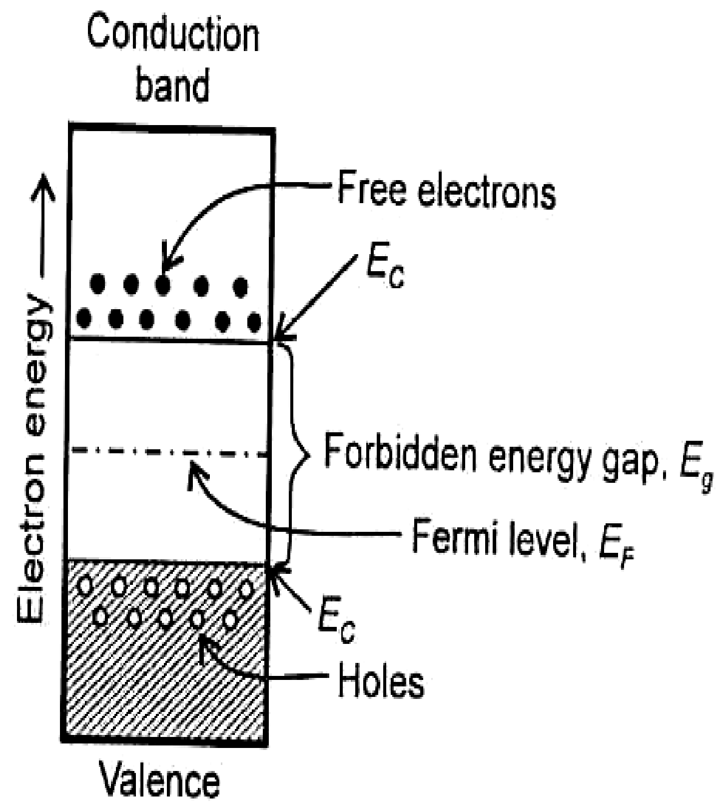


- **Fermi energy level is the maximum energy that a free electron can have at 0^0 K, in a conductor.**
- **On raising the temperature, the total number of electrons remain the same; but some electrons have energy higher than E_F.**

Fermi Energy Level
(In Intrinsic Semiconductor)

- It is defined as the energy that corresponds to the centre of gravity of the conduction electrons (in CB) and holes (in VB), weighted according to their energies.

- Thus, in an intrinsic semiconductor it lies in the middle of the forbidden energy gap.



Forbidden energy gap, $E_g = E_C - E_V$

Fermi energy level, $E_F = \dfrac{E_C + E_V}{2}$

Types of Extrinsic Semiconductors

- **Donor or *N*-type**

  If a pentavalent atom (e.g., As, Sb, P) replaces the tetravalent Ge or Si atoms in the crystal lattice, donor or *N*-type Extrinsic type Semiconductor is formed.

  $n >> p$

- **Acceptor or *P*-type**

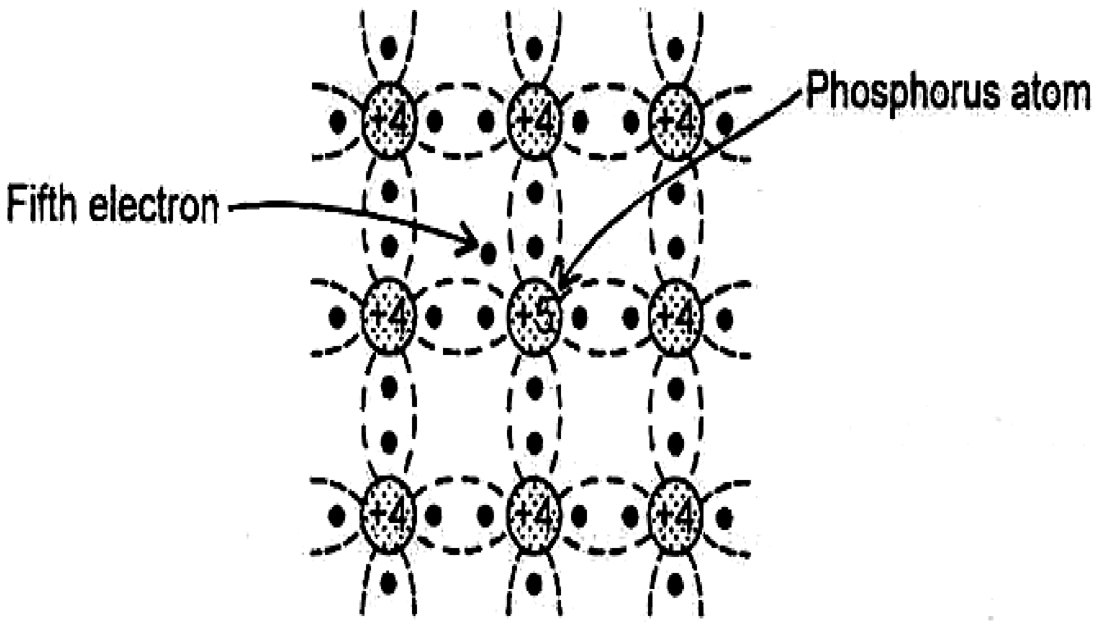
  If a trivalent atom (e.g. B, Ga, In) replaces tetravalent Ge or Si atoms in the crystal lattice, acceptor or *P*-type Extrinsic type Semiconductor is formed.

  $p >> n$

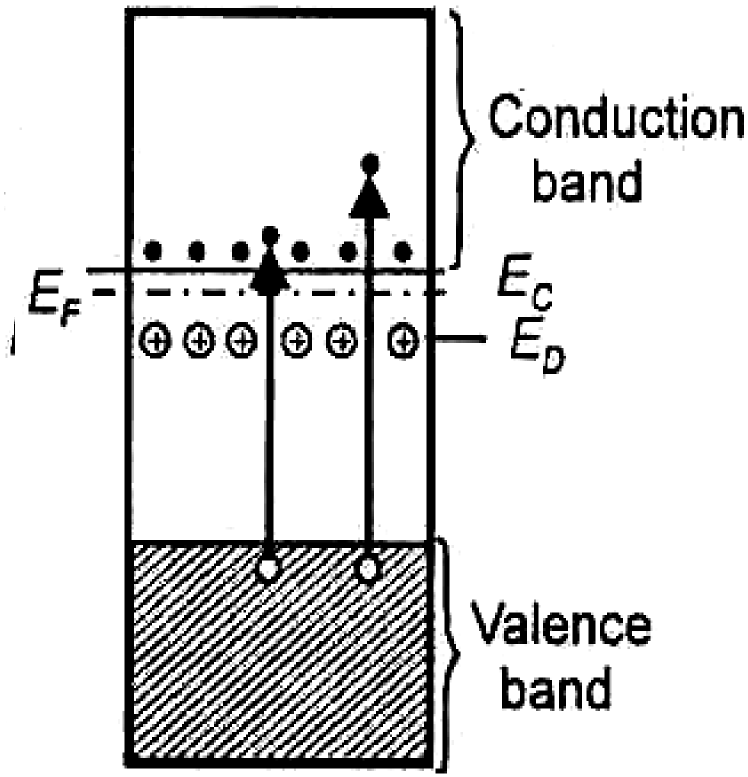
Mass-Action Law: The product of the free negative and positive concentration is constant and is independent of the amount of donor and acceptor impurity doping for a material, i.e., $n.p = n_i^2$

Donor or *N*-type Semiconductors

- Four of the five electrons make the covalent bonds.
- The fifth is loosely bound to the nucleus.
- The energy required to detach this fifth electron from the atom is of the order of only 0.01 eV for Ge and 0.05 eV for Si.
- The impurity atom becomes a positive immobile ion.
- Not only the number of electrons increases in the n-type semiconductor, but the number of holes decreases below the intrinsic value.



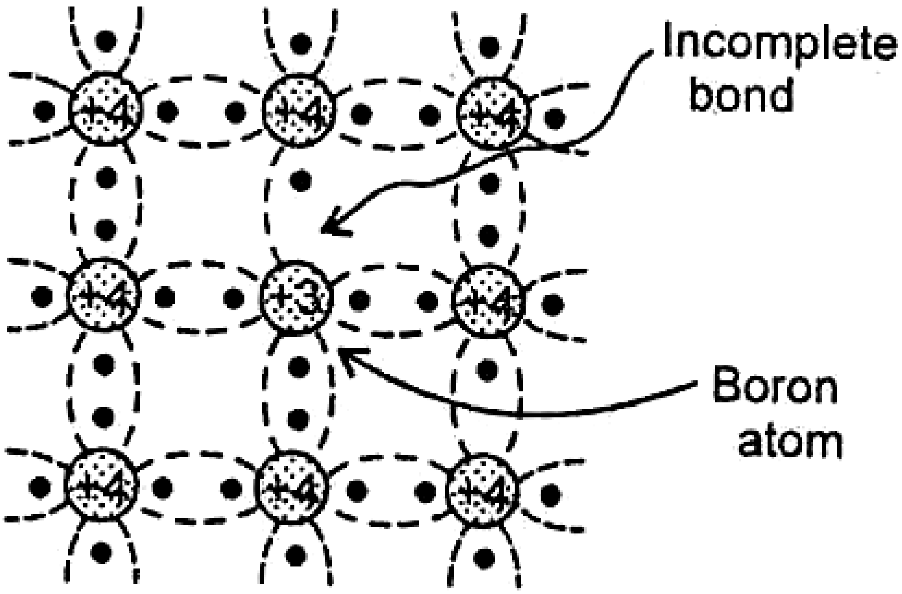
(a) Crystalline structure



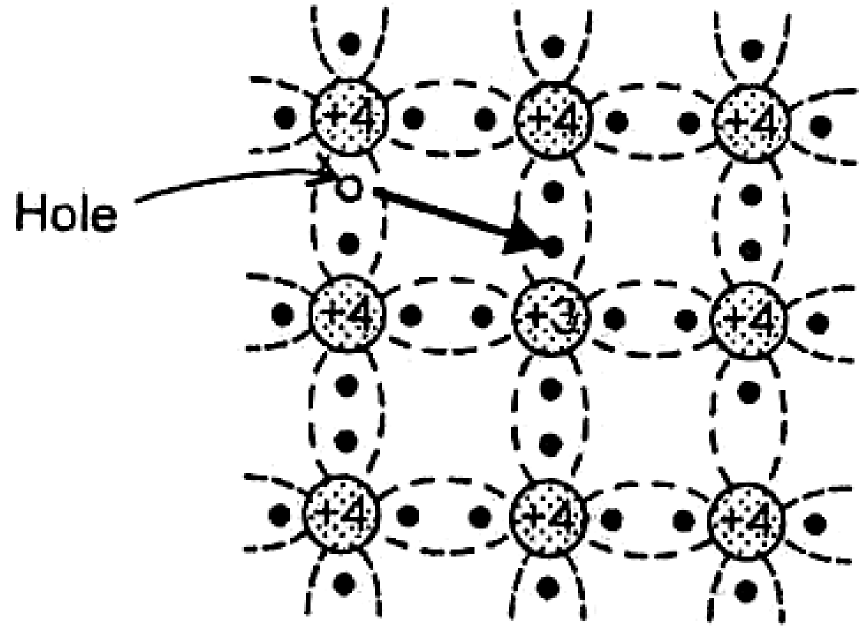
(b) Energy band diagram.

Acceptor or *P*-type Semiconductors

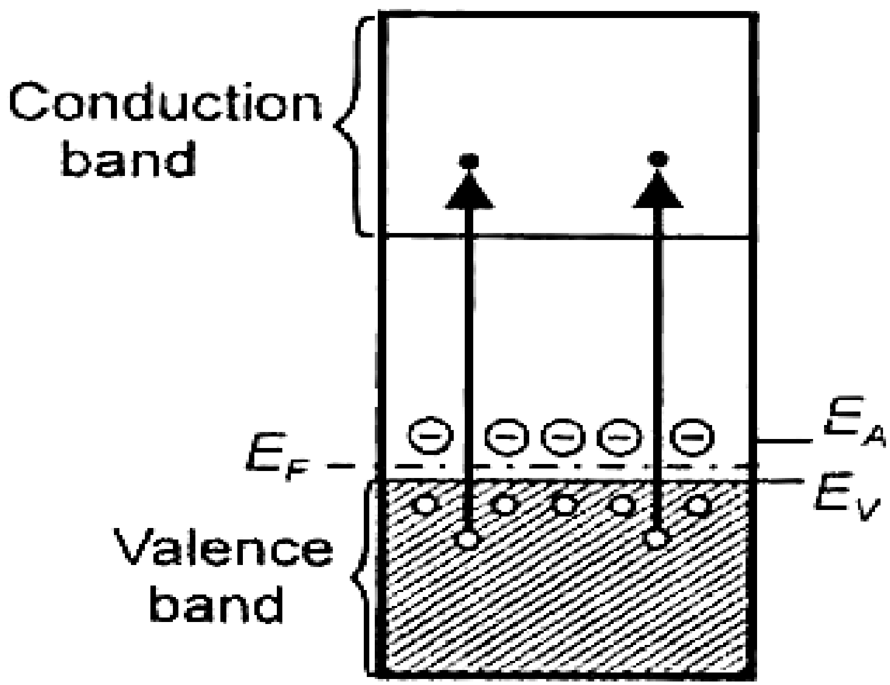
- Only three of the covalent bonds can be filled.
- There remains a vacancy in the fourth bond.
- Is this vacancy a hole ?
- Ans. No.
- The single electron in the incomplete bond has a great tendency to snatch an electron from a neighbouring bond.
- Only a little energy ($\approx$ 0.01 eV) is needed for the electron from a neighbouring bond to jump to this vacancy.
- When this happens a hole is created.
- Not only the number of holes increases in the *P*-type semiconductor, but the number of electrons decreases below the intrinsic value.



(*a*) Boron added to silicon



(*b*) Creation of a hole



Charge Equation for N-type materials

$$N_D \quad + \quad p \quad = \quad n$$

(+ve ions) (holes) (electrons)

Hence,

$$n >> p$$

Charge Equation for P-type materials

$$N_A \quad + \quad n \quad = \quad p$$

(-ve ions) (electrons) (holes)

Hence,

$$p >> n$$

Total positive charge density = $N_D + p$
Total negative charge density = $N_A + n$
According to electrical neutrality,

$$N_D + p = N_A + n$$

In case of *N*-type material having $N_A = 0$
and $n_n >> p_n$,
The equation for electrical neutrality becomes,

$$N_D + p_n = N_A + n_n$$

i.e. $n_n \approx N_D$

- **In an *N*-type material the free electron concentration is approximately equal to the density of donor atoms.**

Concentration of holes in *N*-type semiconductor is given by

$$p_n = \frac{n_i^2}{N_D}$$

In case of *P*-type material having $N_D = 0$

and $p_p >> n_p$,

The equation for electrical neutrality becomes,

$$N_D + p_p = N_A + n_p$$

i.e. $$p_p \approx N_A$$

- **In an *P*-type material, the hole concentration is approximately equal to the density of acceptor atoms.**

Concentration of holes in semi-conductor is given by

$$n_p = \frac{n_i^2}{N_A}$$

- It is possible to add donors to *P*-type crystal, or conversely, to add acceptors to *N*-type crystal.

- What happens if equal concentration of donors and acceptors are added to an intrinsic semiconductor ?
- Ans. It remains intrinsic.

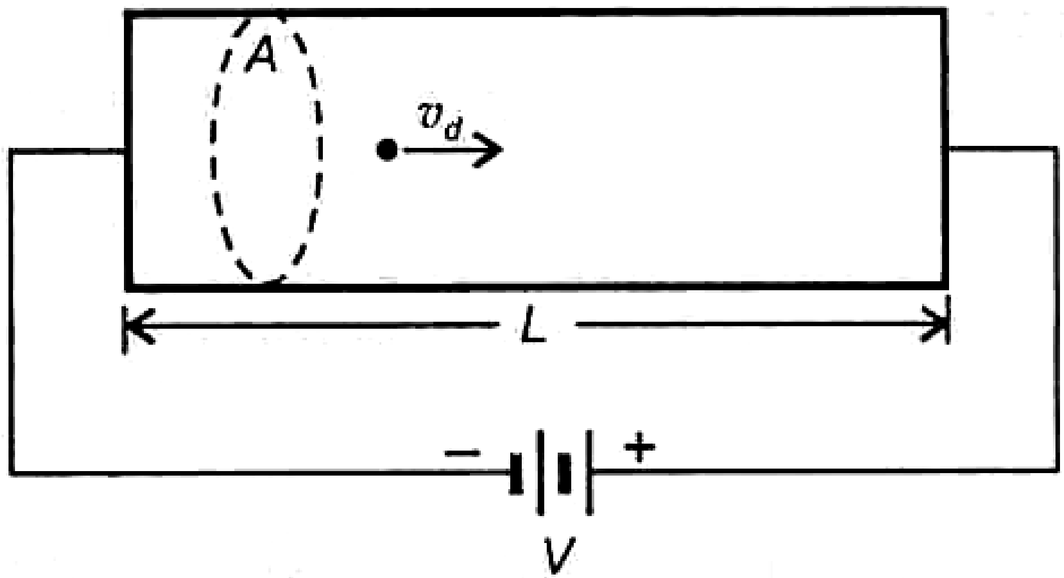
$$N_D = N_A \quad \text{and} \quad n = p$$

Conductivity

- **Let *n* be the concentration of charge carriers.**
- **The time to cross the length is**

$$t = L / v_d$$

- **The drift current is given as**

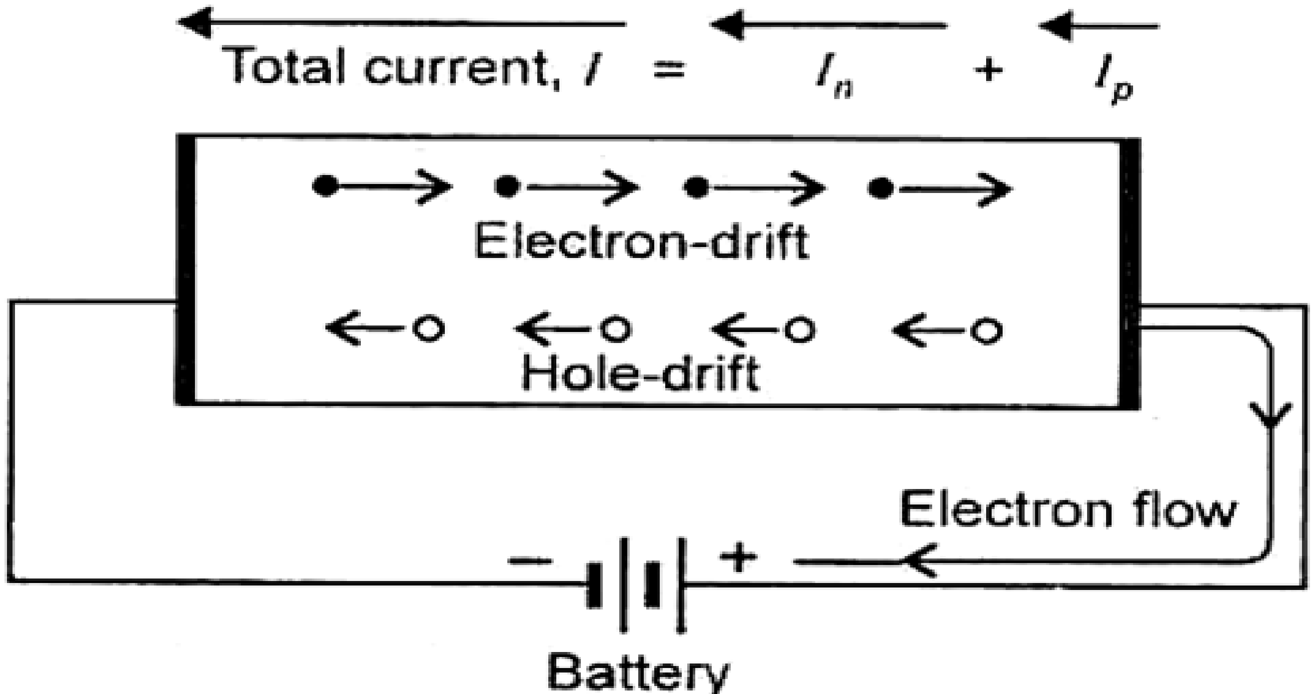


$$I = \frac{Q}{t} = \frac{qnAL}{L/v_d} = qnAv_d = qnA\mu\ E$$

The current Density is $J = \frac{I}{A} = qn\mu\, E$

- Putting σ = *qnμ,* we get, $J = \sigma E$
- This is simply *Ohm's Law,* in another form.
- The constant σ is called Conductivity.

Conduction in Intrinsic Semiconductors
(Drift of electrons and holes in an external field)



- When an external voltage is applied, electrons move towards the positive electrode and the holes towards the negative electrode. The drift of electrons in the conduction band and that of holes in the valence band produce an electric current.

- **Electron-drift current I_n is greater than the hole-drift current I_p.**

$$I_n = \frac{Q_n}{t} = \frac{(qn)(Av_n)}{1} = qnAv_n$$

$$I_p = \frac{Q_p}{t} = \frac{(qp)(Av_p)}{1} = qpAv_p$$

Total Current,

$$I = I_n + I_p = qnAv_n + qpAv_p = q(nv_n + pv_p)A$$

But $v_p = \mu_p E = \mu_p(V/L)$. Therefore,

$$I = q(n\mu_n + p\mu_p)\left(\frac{V}{L}\right)A = q(n\mu_n + p\mu_p)\frac{A}{L}V$$

Applying Ohm's Law,

$$R = \frac{V}{I}$$

$$\rho\frac{L}{A} = \frac{1}{q(n\mu_n + p\mu_p)(A/L)}$$

$$\rho = \frac{1}{q(n\mu_n + p\mu_p)} \quad \Omega\text{m}$$

$$\sigma = \frac{1}{\rho} = q(n\mu_n + p\mu_p) \quad \text{S/m}$$

Since in an intrinsic semiconductor, $n = p = n_i$,

$$\sigma = qn_i(\mu_n + \mu_p) \qquad \text{S/m}$$

Intrinsic Concentration

- With increasing temperature, the density of electron-hole pairs increases and correspondingly conductivity increases.
- It is found that intrinsic concentration n_i varies with T as,

$$n_i = A_0 T^3 \exp\left(-\frac{E_{G0}}{kT}\right)$$

- E_{G0} = Energy gap at 0^0K in electron volts
- k = Boltzman constant in eV/K
- A_0 = a constant independent of T.

Energy Gap or Band Gap

- The forbidden energy gap in semiconductors depends upon temperature.
- Experimentally it has been found that,
  - For Germanium,

$$E_g = 0.785 – 2.23 \text{ X } 10^{-4} T$$

At 300 K, $E_g = 0.72$ eV.

  - For Silicon,

$$E_g = 1.21 - 3.60 \text{ X } 10^{-4} T$$

At 300 K, $Eg = 1.12$ eV.

Diffusion Current Density

- Diffusion hole-current density J_p is proportional to the concentration gradient *dp/dx* and is expressed as

$$J_p = -qD_p \frac{dp}{dx}$$

- This is referred as **Fick's Law.**

- Here *q* is the magnitude of the electronic charge(1.6×10^{-19} coulomb) and D_P is called the ***Diffusion Constant*** or ***Diffusion Coefficient*** or ***Diffusivity***.

- Diffusion does not arise from the mutual repulsion among charged particles of like sign, but it is the result of a **statistical phenomenon.**

- *dp/dx* is negative, as the hole concentration decreases with increase in *x*.Thus, J_p is positive in the positive *x*-direction.

- Similarly, the electron-current density J_n can be written by replacing p by n, D_p by D_n and the minus sign by the plus sign, as

$$J_n = qD_n \frac{dn}{dx}$$

- In such a situation, the total current is the sum of the drift current and the diffusion current.
- Thus,

$$J_p = pq\mu_p E - qD_p \frac{dp}{dx}$$

$$J_n = nq\mu_n E + qD_n \frac{dn}{dx}$$

Einstein Relationship

Since both diffusion and mobility are statistical thermodynamic phenomena, *D* and *μ* are not independent. The relationship between them is given by the Einstein equation:

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T$$

where V_T is the voltage equivalent of temperature, defined by,

$$V_T \equiv \frac{\bar{k}\,T}{q} = \frac{T}{11600}$$

- Here $\bar{k}$ is the Boltzman Constant in J/K. (*k* is the Boltzman Constant in eV/K).

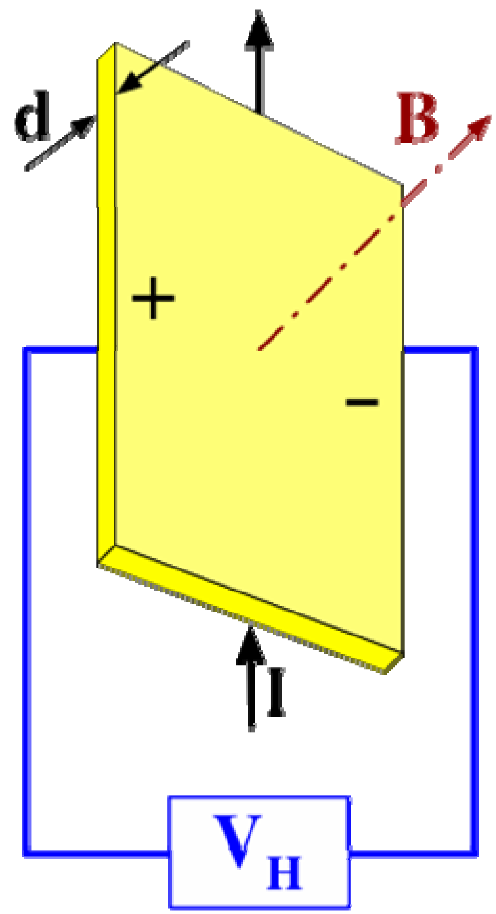
$$=1.60\text{X}10^{-19}k$$

At room temperature (300 K), $V_T = 0.026$ V

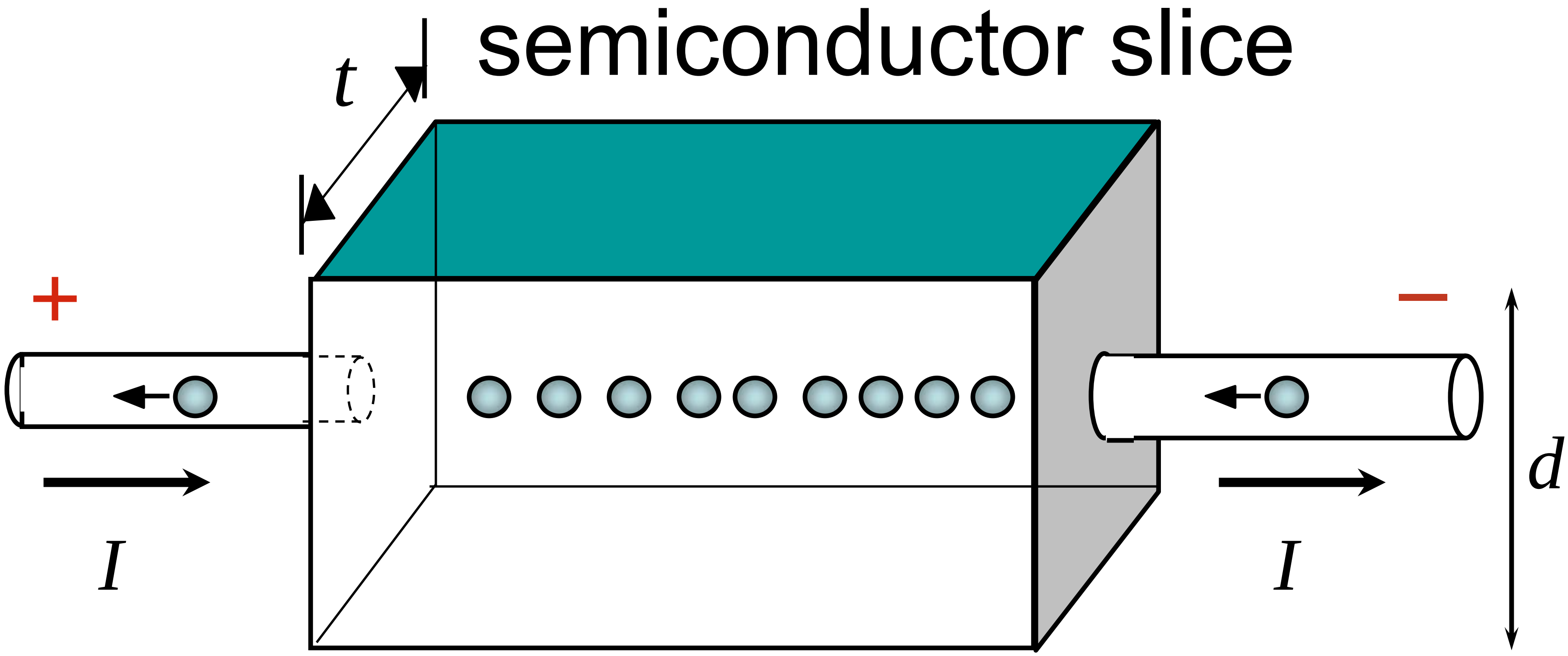
= 26 mV

HALL EFFECT

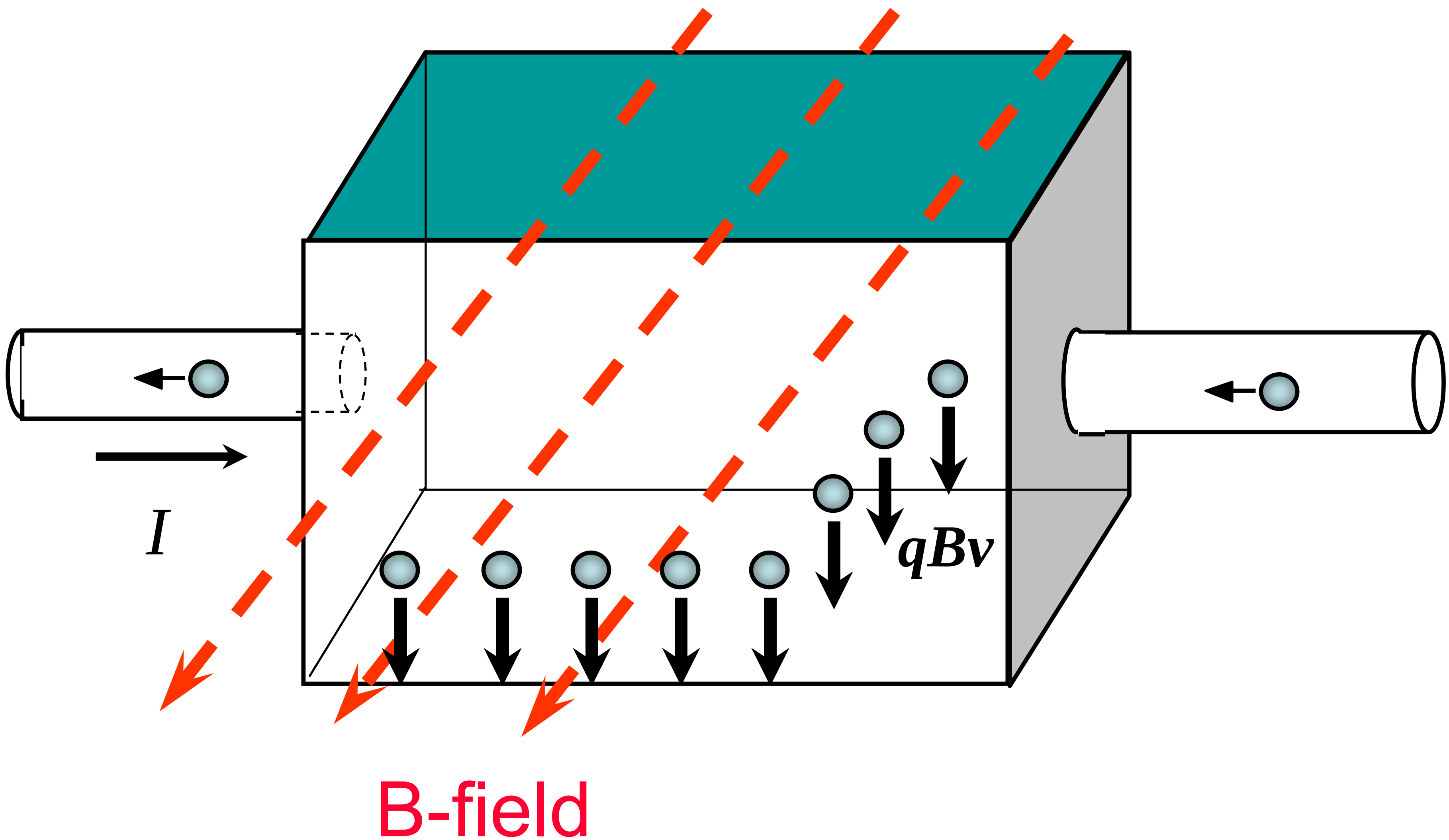
- Moving charges experience Lorentz force, when a magnetic field is present perpendicular to their motion.
- When such a magnetic field is absent, the charges follow approximately straight, 'line of sight' paths.
- However, when a perpendicular magnetic field is applied, their paths are curved so that moving charges accumulate on one face of the material.
- This leaves equal and opposite charges exposed on the other face, where there is a scarcity of mobile charges.
- The result is an asymmetric distribution of charge density across the Hall element that is perpendicular to both the 'line of sight' path and the applied magnetic field.
- The separation of charge establishes an electric field that opposes the migration of further charge, so a steady electrical potential builds up for as long as the charge is flowing.



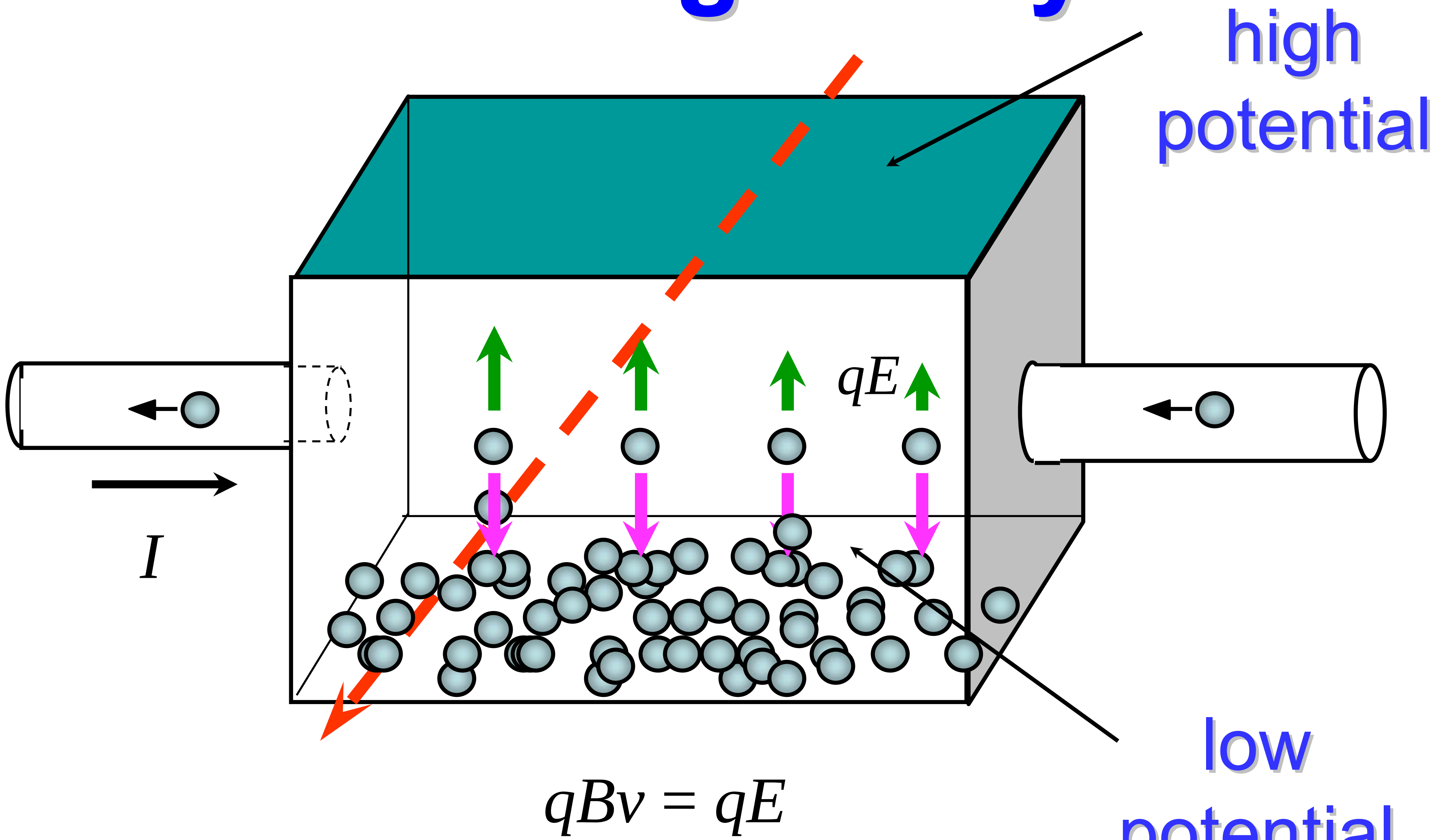
When electrons flow without magnetic field...



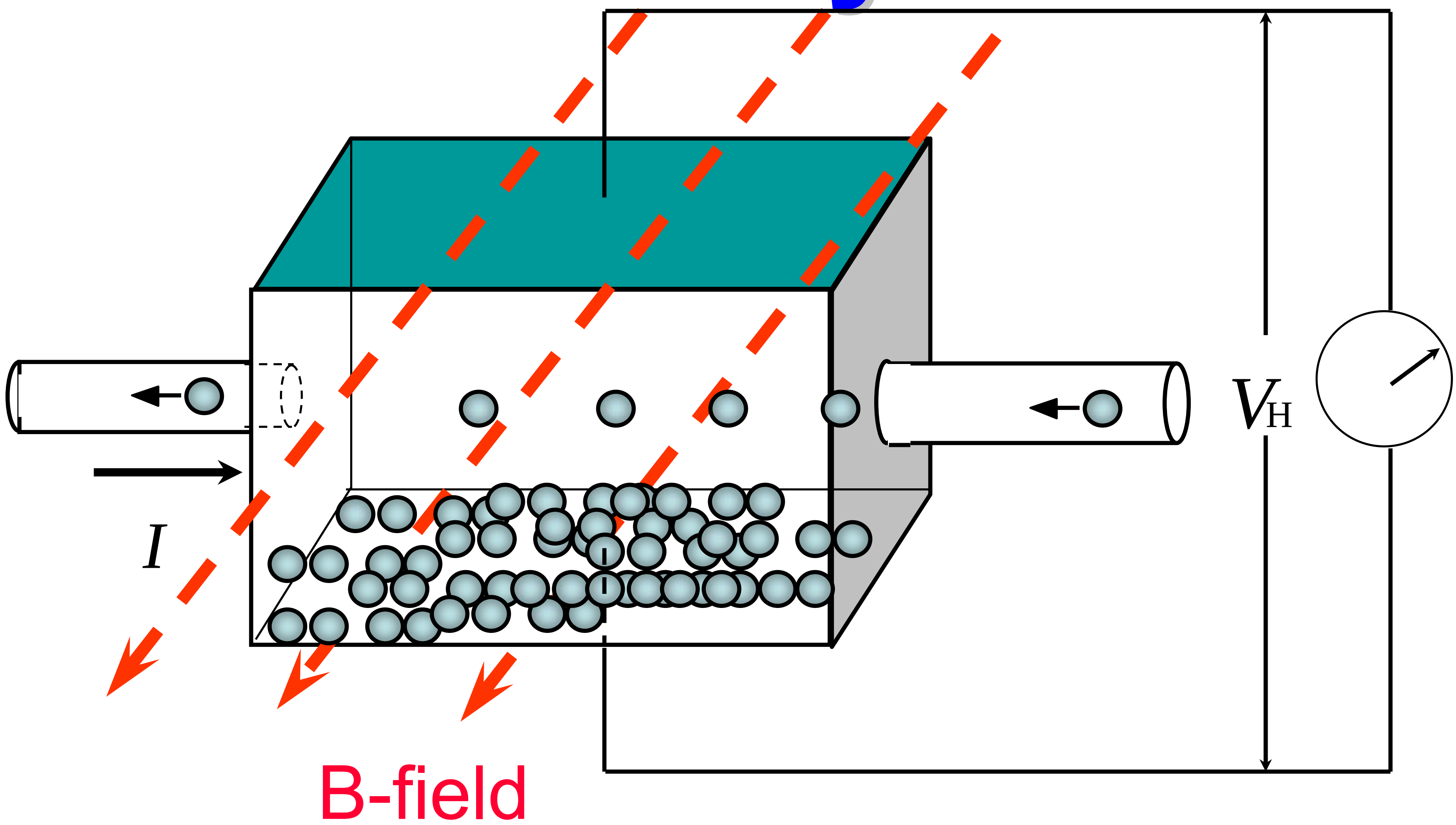
When the magnetic field is turned on ...



As time goes by...



Finally...



- For a simple metal where there is only one type of charge carrier (electrons) the Hall voltage V_H is given by

$$V_H = \frac{-IB}{dne}$$

- The Hall coefficient is defined as

$$R_H = \frac{E_y}{j_x B}$$

- where j_x is the current density of the carrier electrons in X-direction, and E_y is the induced electric field in Y-direction for magnetic field to be in Z-direction. In SI units, this becomes

$$R_H = \frac{E_y}{j_x B} = \frac{dV_H}{IB} = -\frac{1}{ne}$$

- As a result, the Hall effect is very useful as a means to measure either the carrier density or the magnetic field.

Hall effect in semiconductors

- When a current-carrying semiconductor is kept in a magnetic field, the charge carriers of the semiconductor experience a force in a direction perpendicular to both the magnetic field and the current. At equilibrium, a voltage appears at the semiconductor edges.

- The simple formula for the Hall coefficient given above becomes more complex in semiconductors where the carriers are generally both electrons and holes which may be present in different concentrations and have different mobilities. For moderate magnetic fields the Hall coefficient is

$$R_H = \frac{-n\mu_e^2 + p\mu_h^2}{e(n\mu_e + p\mu_h)^2}$$

- For large applied fields the simpler expression analogous to that for a single carrier type holds.

$$R_H = \frac{(p - nb^2)}{e(p + nb)^2}$$

- with

$$b = \frac{\mu_e}{\mu_h}$$