ECE 111

Carrier motion in Semiconductors
Drift and diffusion currents (2)

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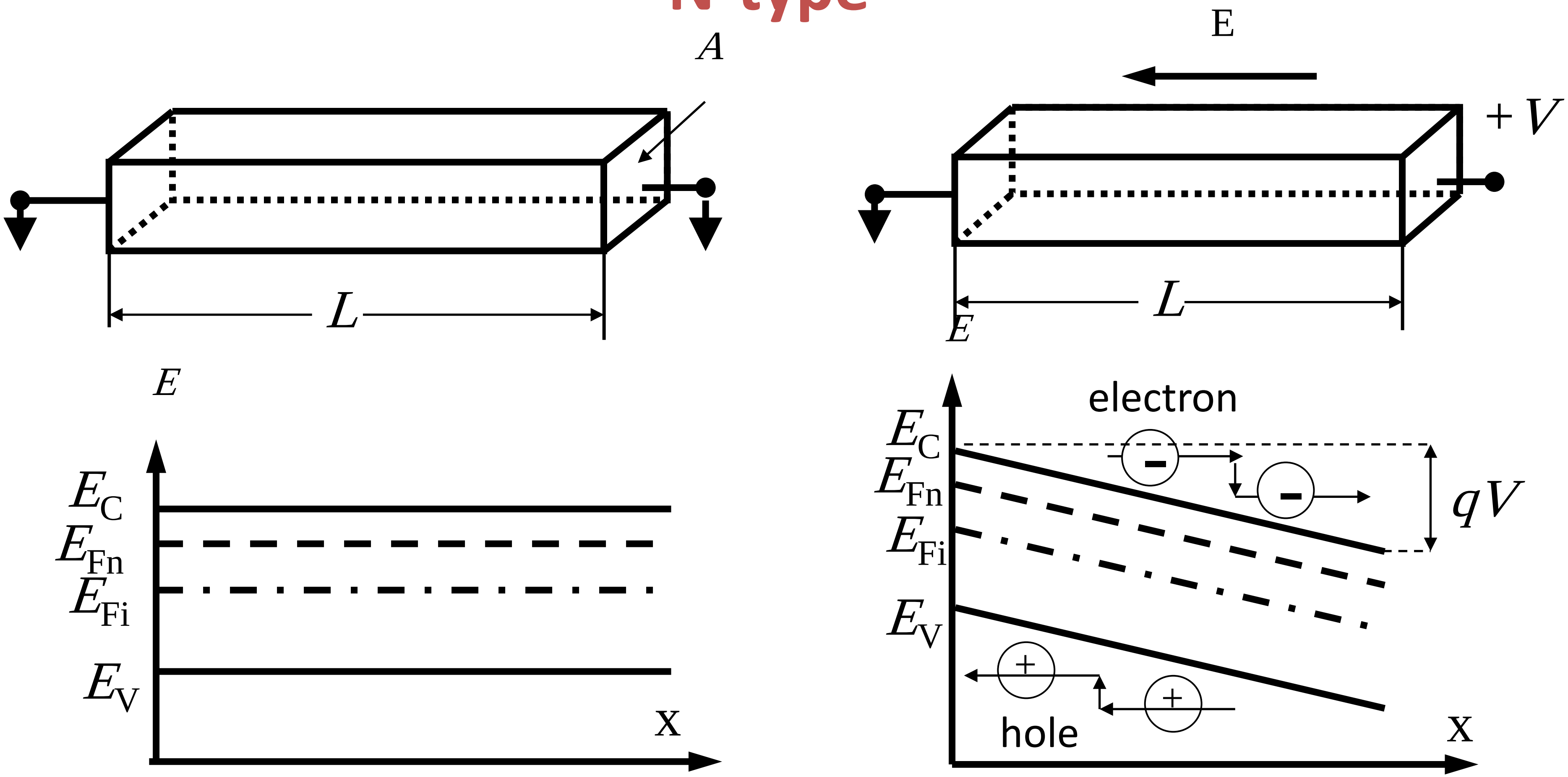
Drift Current

The current produced by the transport of carriers under the influence of an applied electric field is called the drift current.

N-type



Electric potential

$$-q\mathbf{E} = -\frac{dE_C}{dx} = -\frac{dE_i}{dx} = -\frac{dE_V}{dx}$$

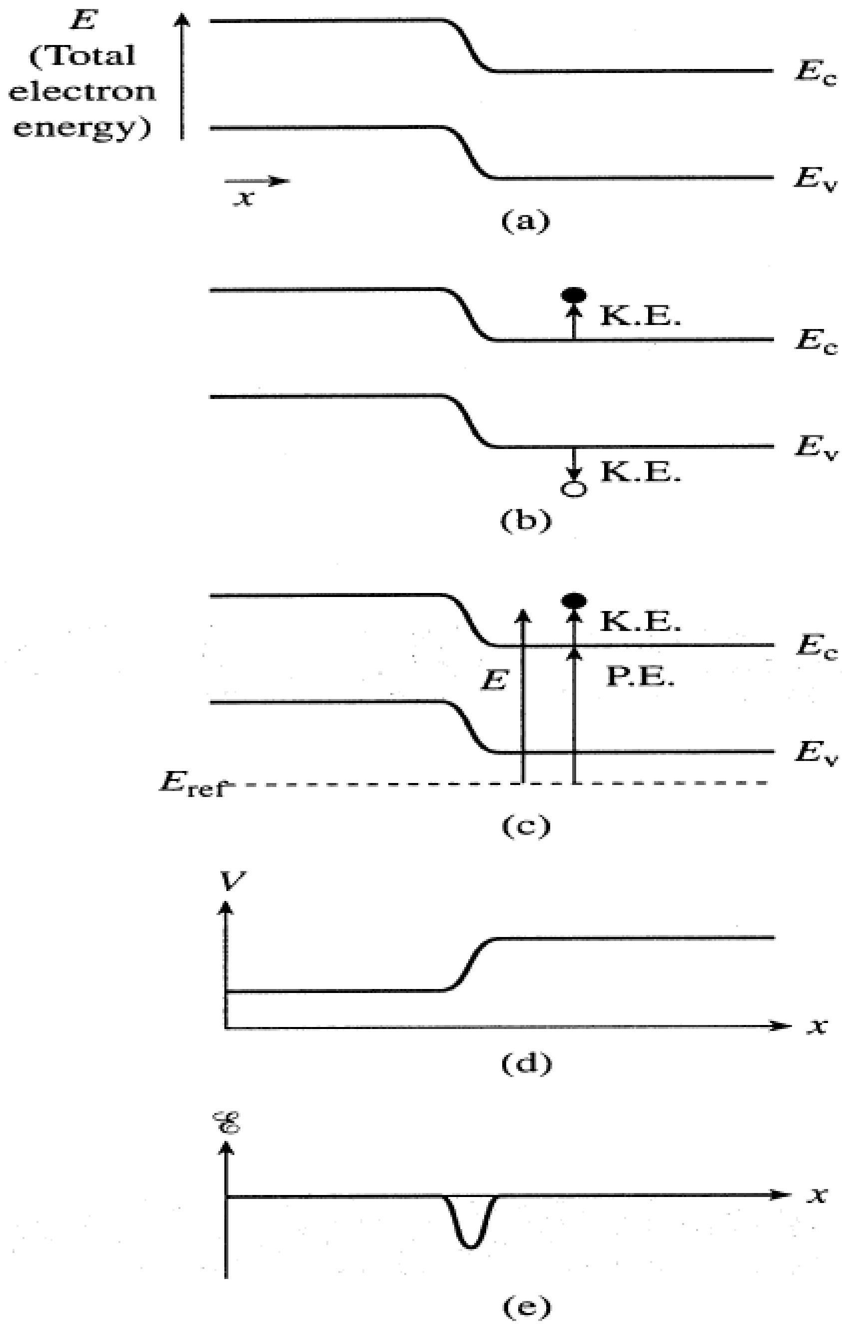
$$\mathbf{E} = \frac{1}{q}\frac{dE_C}{dx} = \frac{d}{dx}\left(\frac{1}{q}E_{Fi}\right)$$

Relation between Electric field and electric potential

$$\mathbf{E} \equiv -\frac{d\varphi}{dx}$$

$$\boxed{\varphi = -\frac{E_{Fi}}{q}}$$

Band Bending



(a) Sample energy band diagram;

(b) Carrier kinetic energies;

(c) Electronic potential energy;

(d) Potenital;

(e) Electric field.

drift current density

$$v_n = -\mu_n \mathbf{E}$$

$$v_p = \mu_p \mathbf{E}$$

$$J_n = -q\,n\,v_n = q\,n\,\mu_n\,\mathbf{E}$$

$$J_p = q\,p\,v_p = q\,p\,\mu_p\,\mathbf{E}$$

$$\boxed{J = J_n + J_p = q\left(n\mu_n + p\,\mu_p\right)\mathbf{E}}$$

$$J = q\left(n\mu_n + p\,\mu_p\right)\mathbf{E}$$

$$\boxed{\sigma = q\left(n\mu_n + p\,\mu_p\right)} \qquad \rho = \frac{1}{\sigma}$$

Ohm's law: $J = \sigma\,\mathbf{E}$

Diffusion

&

Diffusion Current Density

Diffusion in semiconductors

So far we considered the drift motion of carriers in semiconductors due to applied electric fields. That motion gives rise to drift current.

- There is another type of current in semiconductors that arises due to the **diffusion of carriers**. Diffusion is also a consequence of random thermal motion of carriers. But the exact source of diffusion is the **non-uniform spatial distribution of carriers**.
- We have assumed so far that the carrier concentration distribution is uniform everywhere inside the semiconductor. This may not always be true. For example, the impurity distribution inside a semiconductor may vary due to processing conditions. There may be different types of impurities in different regions that will also give rise to non-uniform carrier distribution.
- Let us now analyze the consequence of non-uniform distribution of carriers.

Origin of diffusion Concentration gradients

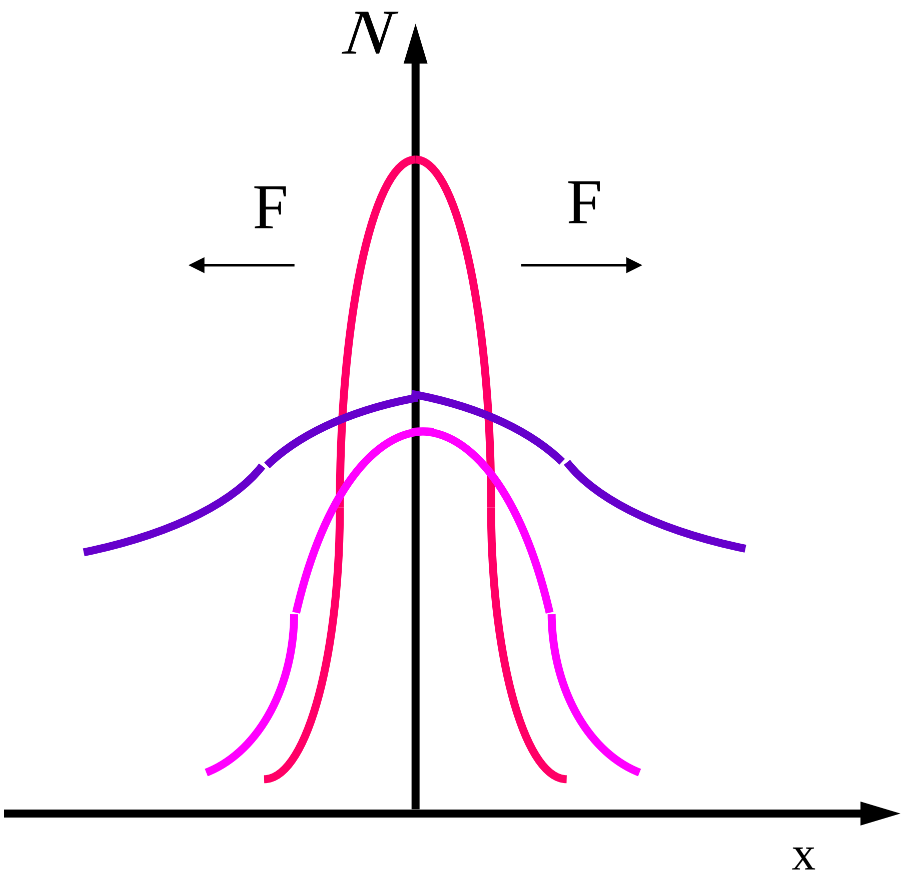
- When the carrier concentration is uniform everywhere inside a semiconductor sample, the carriers **move in and out** of any small region at the same rate due to the random thermal motion.

- However, when carrier concentration is non-uniform, **more** number of **carriers move out** of the higher carrier concentration region **than** the number of **carriers that move into** it. As a result, there is a net motion of carriers from the higher concentration region to a lower concentration region. Thermal agitation causes the carriers to spread in such a way as to equalize the distribution. This motion of carriers is known as the **diffusion.**

- Thus, the two main factors that are responsible for diffusion are **the thermal agitation** and the **concentration differences.**

diffusion

Fick's law describes diffusion as the flux, F, (of particles in our case) is proportional to the gradient in concentration.



$$F = -D\frac{dN}{dx}$$

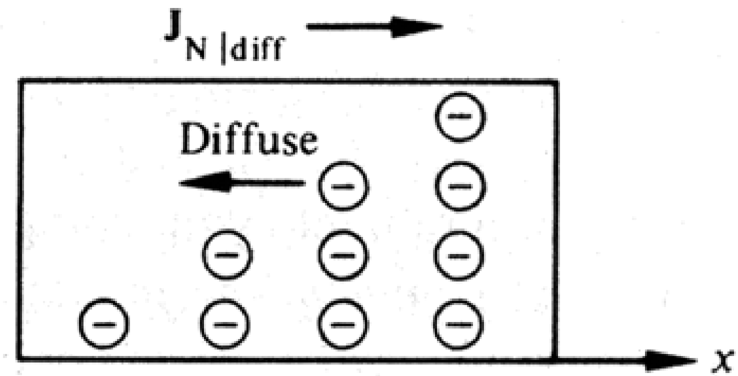
F – flux of carriers

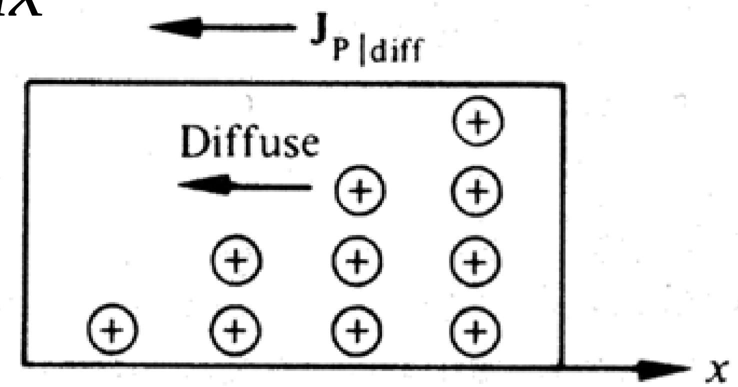
N – carrier density

D – diffusion constant (diffusivity)

Diffusion current

$$Flux = F = -D\frac{dN}{dx}$$





$$J_{ndiff} = -q\left(-D_n\frac{dn}{dx}\right)$$

$$\boxed{J_n = qD\frac{dn}{dx}}$$

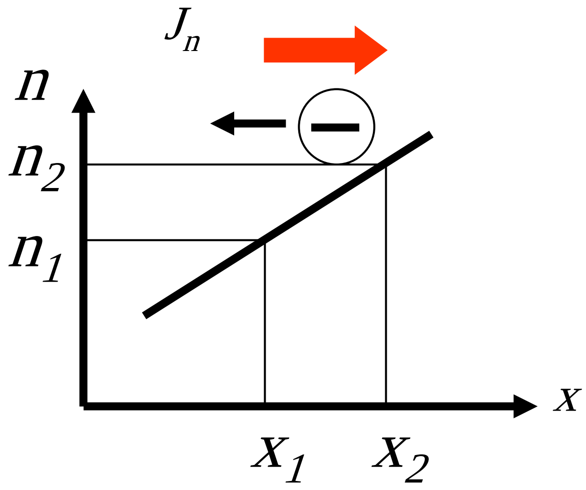
$$\boxed{J_p = -qD_p\frac{d\,p}{d\,x}}$$

Diffusion current

Electrons

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

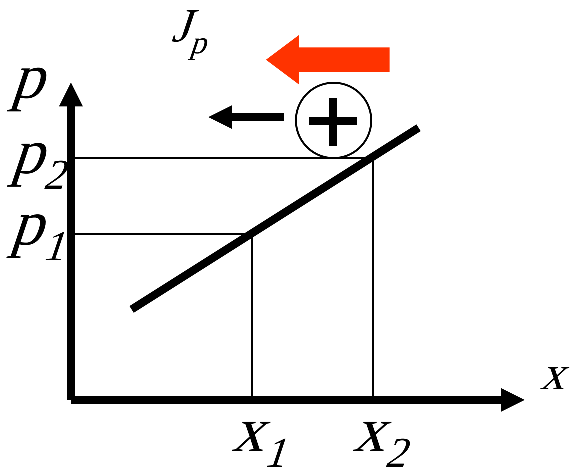
D_n diffusion constants for electrons



Holes

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

D_p diffusion constants for holes



Einstein's relationship

$$n = n_i \exp\left(\frac{E_F - E_i}{kT}\right)$$

$$\mathbf{E} = \frac{1}{q}\frac{dE_i}{dx}$$

for thermal equilibrium: $$J_n = q\mu_n n\mathbf{E} + qD_n \frac{dn}{dx} = 0$$

$$\cancel{q}\mu_n \cancel{n_i \exp\left[\frac{E_F - E_i}{kT}\right]} \frac{1}{q} \cancel{\frac{dE_i}{dx}} = -\frac{\cancel{q}}{kT} D_n \cancel{n_i \exp\left[\frac{E_F - E_i}{kT}\right]} \left[\frac{dE_F}{dx} - \cancel{\frac{dE_i}{dx}}\right]$$

$$\frac{dE_F}{dx} = 0$$

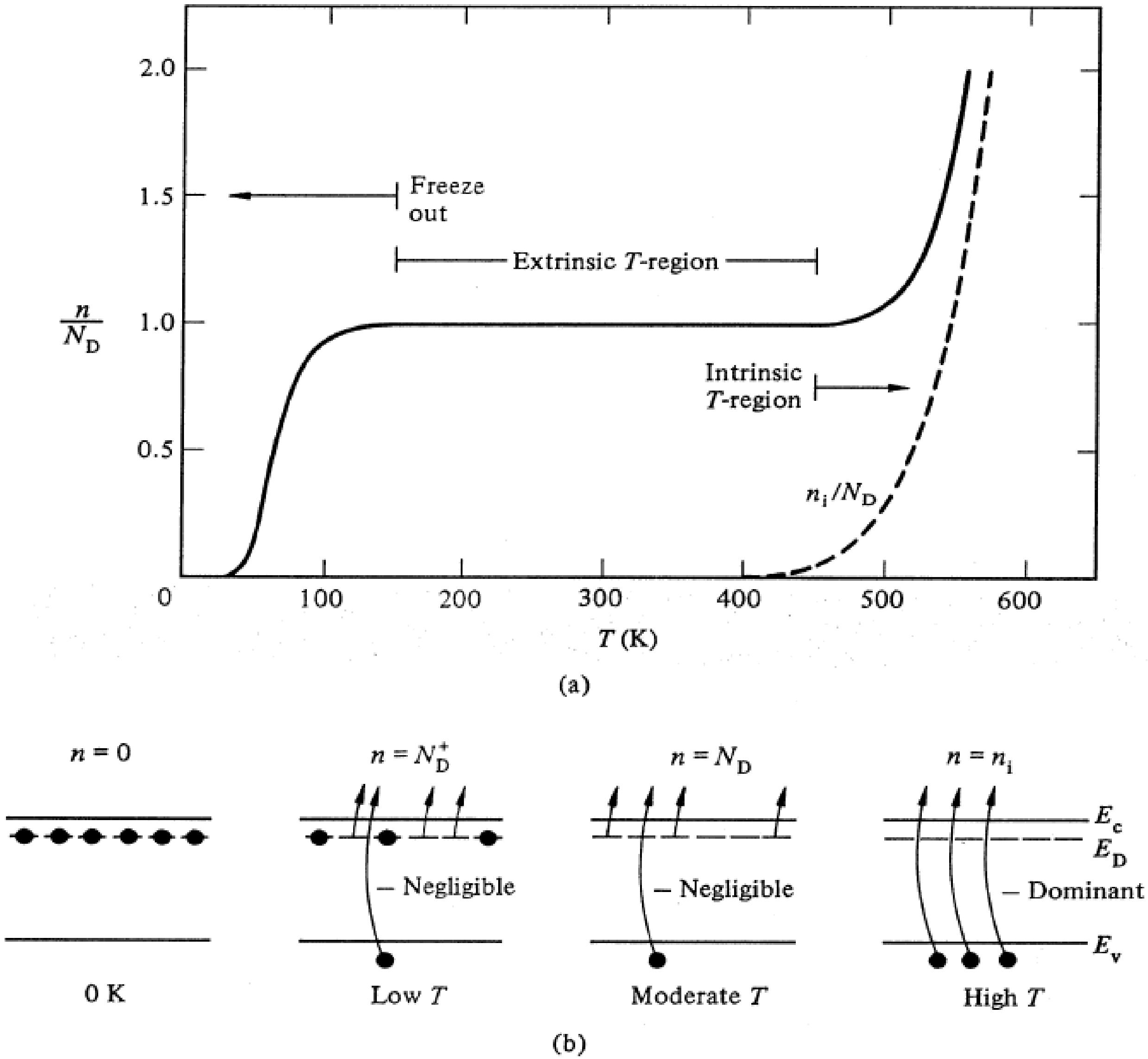
$$\mu_n = \frac{qD_n}{kT}$$

$$\boxed{\frac{D_n}{\mu_n} = \frac{kT}{q} = V_T}$$

V_T thermal potential

Good luck

Note: (Carriers at equilibrium)
Carrier Concentration Temperature Dependence



Temperature dependence of carrier concentrations

- **Freeze-out region:** (Very low temperatures, typically below 100K) Carrier concentration gradually increases as the T is increased as the impurity ionization increases.

- **Extrinsic region:** (intermediate temperatures) – Ionization of the impurities is complete. Carrier concentration is constant. Intrinsic carrier concentration is much smaller than the doping concentration.

- **Intrinsic region:** (Very high temperatures) – Intrinsic carrier concentration is higher than the doping concentration. Electron and hole concentrations are equal. The material behaves as if intrinsic.