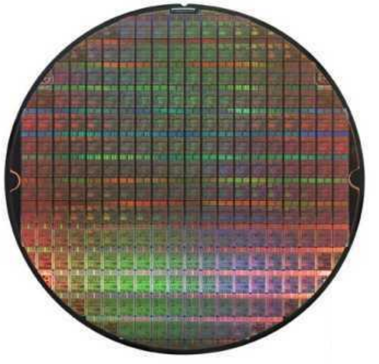


Module – II.1

Carrier Diffusion

Diffusion Current:

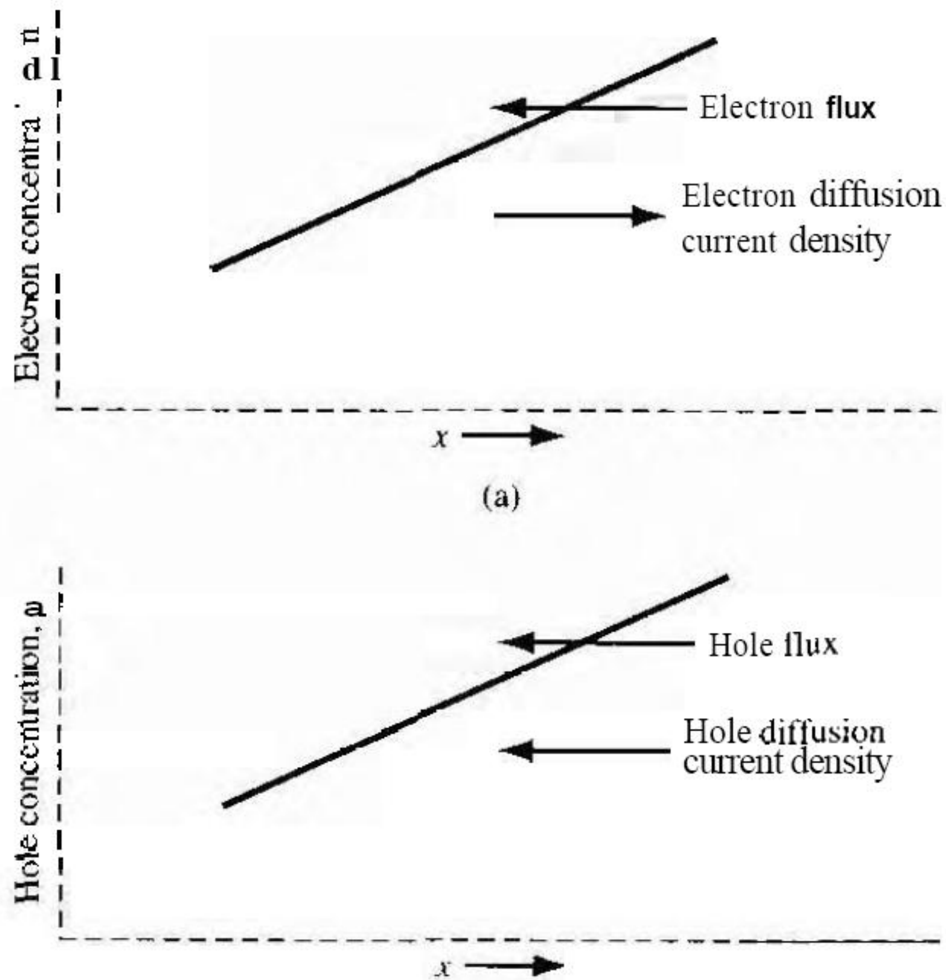
If there is a gradient of concentrations of carriers, they can move by diffusion determined by Fick's Laws of Diffusion. This gives diffusion current density, J^{diff}.

In metals, as conductivity is high diffusion is not important, but low conductivity and the ease of creating non-uniform carrier densities in semiconductors, diffusion an important process .

$$\textbf{For electrons and in one dimension, } J_n^{diff} = qD_n \frac{dn}{dx}$$

$$\textbf{For holes, } J_p^{diff} = -qD_p \frac{dp}{dx}$$

'**q**' is the elementary charge
(+1.6 × 10^{-19} C), and $\mathbf{D_n}$ & $\mathbf{D_p}$ are called the electron & hole **diffusion constant.**



For positive dn/dx (n increases as x increases) and positive dp/dx, electrons and holes diffuse to the left (toward the lower concentration point).

Since electrons carry negative charge, the diffusion current flows to the *right.*

But since holes are positively charged, the hole current flows to the *left*, the current is negative.

Current through a semiconductor can flow through drift and/or diffusion. So total current is given as:-

$$J_n = J_{n,\mathrm{drift}} + J_{n,\mathrm{diffusion}} = qn\mu_n\mathscr{E} + qD_n\frac{\mathrm{d}n}{\mathrm{d}x}$$

$$J_p = J_{p,\mathrm{drift}} + J_{p,\mathrm{diffusion}} = qp\mu_p\mathscr{E} - qD_p\frac{\mathrm{d}p}{\mathrm{d}x}$$

$$J = J_n + J_p$$

$$In\ three\ \mathbf{dim.}$$

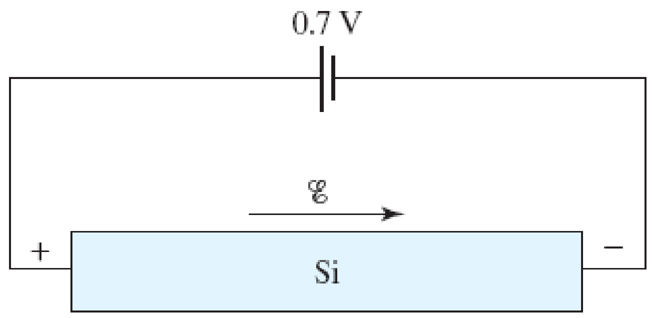
$$J_n = electron\ current$$

$$= J_n^{drift} + J_n^{diff} = qn\mu_n\mathrm{E} + qD_n\nabla n$$

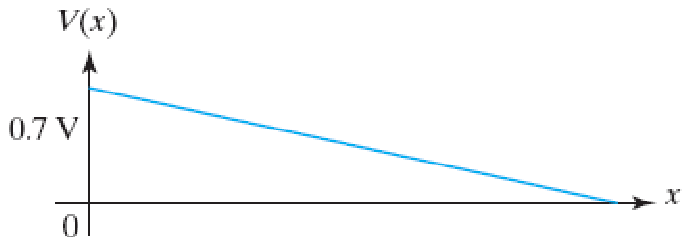
$$\&\ J_p = hole\ current = J_p^{drift} + J_p^{diff}$$

$$= qp\mu_p\mathrm{E} - qD_p\nabla p$$

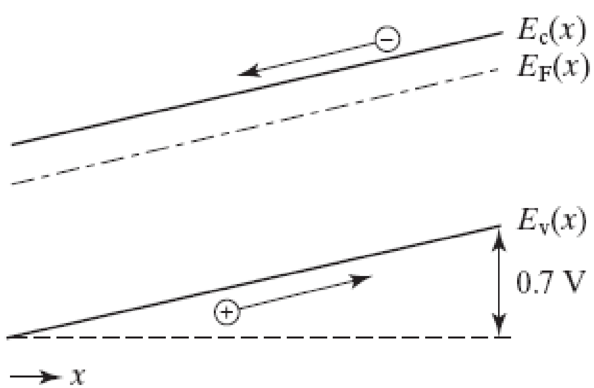
When a voltage is applied across a piece of semiconductor



(a)



(b)

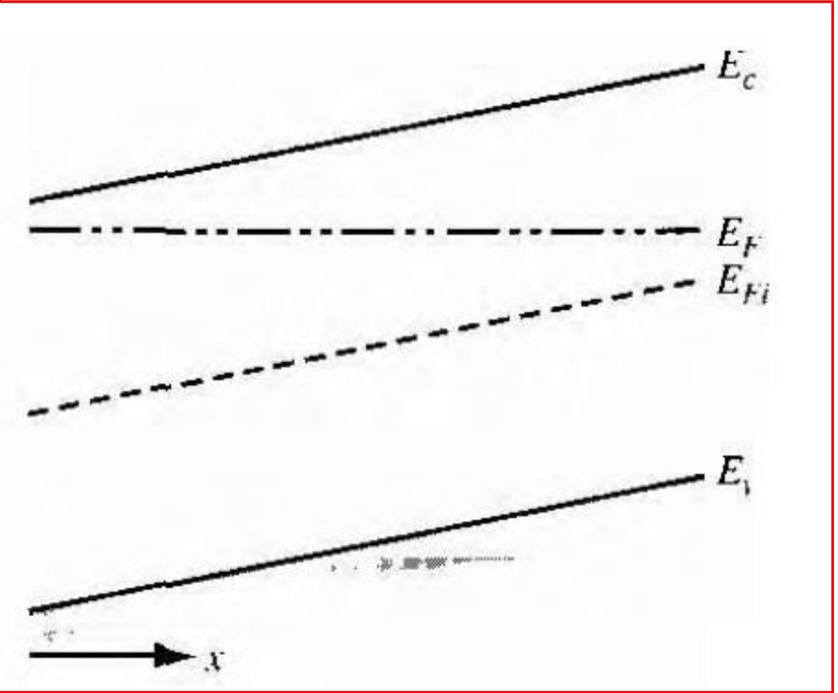


(c)

- ➢A positive voltage raises the potential energy of a positive charge and lowers the energy of a negative charge. It therefore lowers the energy diagrams since the energy diagram plots the energy of an electron (a negative charge)
- ➢So energy diagram is lower (at the left) where the voltage is higher. The band diagram is higher where the voltage is lower.
- ➢**The electrons roll downhill like stones in the energy band diagram and the holes float up like bubbles.**

Graded Impurity Distribution

- Let a semiconductor is non-uniformly doped with donor impurity atoms & the semiconductor is in thermal equilibrium. So the Fermi energy level is constant.
- The doping concentration decreases as 'x' increases.
- There will be a diffusion of majority carrier electrons from the region of higher conc. to low conc. (to right).
- Negative electrons leaves behind positively charged donor ions. So separation of positive and negative charge induces an electric field in +x direction.
- When equilibrium is reached, the induced electric field prevents any further separation of charge.



So electric potential

$$V = \frac{1}{e}(E_F - E_{Fi})$$

So electric field

$$\mathbf{E} = -\frac{dV}{dx} = \frac{1}{e}\frac{dE_{Fi}}{dx}$$

If electron concentration is almost equal to the donor impurity concentration

$$n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right] \approx N_d(x)$$

$$\Rightarrow \quad E_F - E_{Fi} = kT \ln\left(\frac{N_d(x)}{n_i}\right)$$

$$\Rightarrow \quad -\frac{dE_{Fi}}{dx} = \frac{kT}{N_d(x)}\frac{dN_d(x)}{dx}$$

$$\Rightarrow \quad \boxed{\mathrm{E}_x = -\left(\frac{kT}{e}\right)\frac{1}{N_d(x)}\frac{dN_d(x)}{dx}}$$

Einstein Relation:

$$J_n = J_n^{drift} + J_n^{diff} = en\mu_n \mathrm{E} + eD_n \frac{dn}{dx}$$

At equilibrium, J_n = 0

$$J_n = en\mu_n \mathrm{E} + eD_n \frac{dn}{dx} = 0$$

$$If \;\; n \approx N_d$$

$$J_n = e\mu_n N_d(x)\mathbf{E} + eD_n \frac{dN_d(x)}{dx} = 0$$

$$0 = -e\mu_n N_d(x)\left(\frac{kT}{e}\right)\frac{1}{N_d(x)}\frac{dN_d(x)}{dx} + eD_n \frac{dN_d(x)}{dx}$$

$$\frac{D_n}{\mu_n} = \frac{kT}{e}$$

Similarly for hole current $$\frac{D_p}{\mu_p} = \frac{kT}{e}$$

$$\frac{D}{\mu} = \frac{k_B T}{q} \Leftarrow \textbf{Einstein Relation}$$

In semiconductors, $$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{k_B T}{q} \cong 25.87 \text{ mV at } 300\text{K}$$

As the mobilities are strong functions of temperature, the diffusion coefficients are also strong functions of temperature. Major temperature effects are a result of lattice scattering and ionized impurity scattering processes.

	μ_n	D_n	μ_p	D_p
Si	1350	35	480	12.4
GaAs	8500	220	400	10.4
Ge	3900	101	1900	49.2

Using Einstein Relation $\dfrac{D}{\mu} = \dfrac{k_B T}{q}$

$$J_n = qn\mu_n \mathrm{E} + qD_n \nabla n = q\mu_n \left[n\mathrm{E} + \frac{k_B T}{q} \nabla n \right]$$

$$J_p = qp\mu_p \mathrm{E} - qD_p \nabla p = q\mu_p \left[p\mathrm{E} - \frac{k_B T}{q} \nabla p \right]$$

$$J_{total} = J_n + J_p = qn\mu_n \mathrm{E} + qp\mu_p \mathrm{E} + qD_n \nabla n - qD_p \nabla p$$

$$= q(n\mu_n + p\mu_p)\mathrm{E} + k_B T(\mu_n \nabla n - \mu_p \nabla p)$$