Current density $J = ne\, v_d$

$J = ne\mu E$ ---------- (2)
This is in the form of $J = \sigma E$
Where $\sigma = ne\mu$ --------- (3) is conductivity
For electrons $\sigma_n = ne\mu_e$
For holes $\sigma_p = pe\mu_h$

Where μ_e ,μ_h are mobilities of electrons and holes respectively.

$\therefore\ \sigma = ne\mu_e + pe\mu_h$

$= (n\mu_e + p\mu_h)e$

$= n_i(\mu_e + \mu_h)e$ --------- (4) where n_i is called intrinsic carrier concentration.

$$\sigma = 2\left[\frac{2\Pi k_B T}{h^2}\right]^{3/2} \left(m_e^* m_h^*\right)^{3/4} \exp\left(\frac{-E_g)}{2K_BT}\right) (\mu_e + \mu_h)e$$

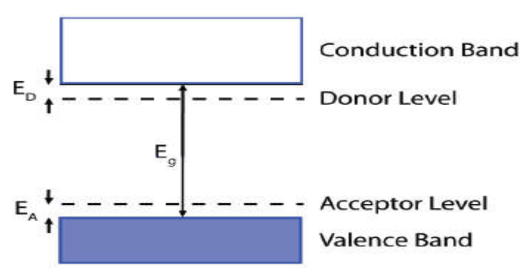
$$\sigma = \sigma_o \exp\left(\frac{-E_g)}{2K_BT}\right) \quad \text{where } \sigma_o = 2\left[\frac{2\Pi k_B T}{h^2}\right]^{3/2} \left(m_e^* m_h^*\right)^{3/4} (\mu_e + \mu_h)e$$

$$\ln\sigma = \ln \sigma_o - \frac{E_g}{2K_BT} \text{ -----------(4)}$$

The above equ. gives the expression for conductivity of intrinsic semiconductor.

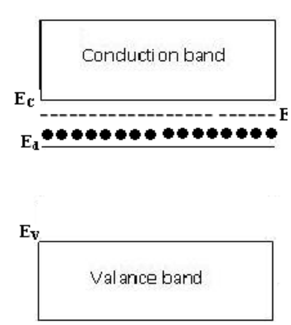
EXTRINSIC SEMICONDUCTORS

To increase the conductivity of pure semiconductors some impurities are added. This process is called doping**.** When impurities are added to semiconductor the available energy levels are altered. One or more energy levels are appeared in the band structure. Doping may create energy levels within the forbidden band.

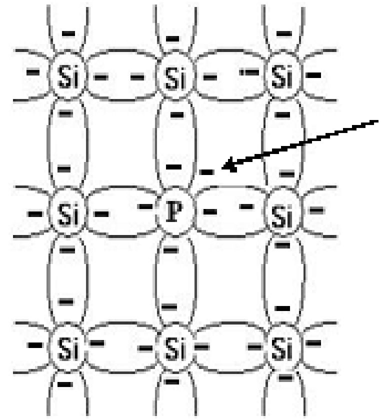


N-TYPE SEMICONDUCTOR

When pentavalent impurities such as phosphorous, Arsenic or Antimony is introduced into Si, or Ge, four of its valence electrons form 4 covalent bonds with other 4 neighboring Si or Ge atoms while the fifth valence electron loosely bound to its nucleus. A small amount of energy is required to detach fifth electron from its nucleus and make it free to conduct. So pentavalent impurities are known as donor impurities. The energy level corresponding to the fifth valence electron lies in the band gap just below the C.B. edge as shown in figure.



ELECTRON CONCENTRATION IN N-TYPE SEMICONDUCTOR

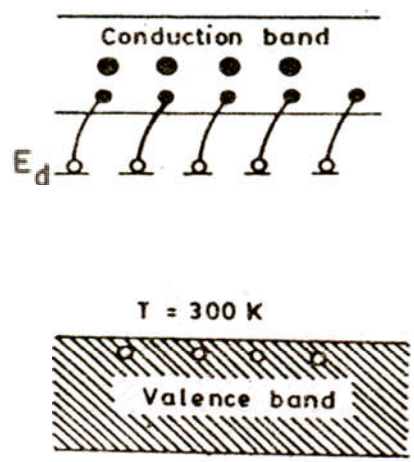


The energy level diagram for n-type semiconductor is shown in fig. At 0k all donor levels are unionized state that is all donor levels are occupied with electrons. As temperature increases slightly some of the donors ionized and contribute electrons to the conduction band. Also some of the valence electrons may jump to the conduction band leaving hole in valence band. The no. of holes produced quite small in this process. Therefore Fermi level must lie near the middle of the donor level and bottom of the conduction band. Let there be N_d donors per unit volume occupying donor levels with energy E_d. The electron concentration in the conduction band is given by

$$n = N_c \exp\left(-\frac{(E_c - E_F)}{K_B T}\right) ---------- (1)$$

The electron concentration must be equal to the sum of concentration of ionized donors in donor levels and concentration of thermally generated holes in valence band. i.e.

$$n = N_d^+ + p ---------------- (2)$$



If donors concentration is high, the holes generated can be neglected.

$$\therefore\ n \approx N_d^+ --------------- (3)$$

The concentration of ionized donors can be written as

$$N_d^+ = N_d[1-F(E_d)]$$

$$= N_d\left[1 - \frac{1}{1 + \exp\left(\frac{E_d - E_F}{K_B T}\right)}\right]$$

$$= N_d\left[\frac{\exp\left(\frac{E_d - E_F}{K_B T}\right)}{1 + \exp\left(\frac{E_d - E_F}{K_B T}\right)}\right]$$

$$= N_d \exp\left[-\left(\frac{E_F - E_d}{K_B T}\right)\right] --------- (4)$$

In n-type semiconductor E_F lies above the E_d, $1 >> \exp\left(\frac{E_d - E_F}{K_B T}\right)$. So exponential term can be neglected in the denominator of the above equation.

From equations (3) and (4), we get

$$N_c \exp\left[-\left(\frac{E_c - E_F}{K_B T}\right)\right] = N_d \exp\left[-\left(\frac{E_F - E_d}{K_B T}\right)\right]$$

$$\exp\left(\frac{-E_c + E_F + E_F - E_d}{K_B T}\right) = \frac{N_d}{N_c}$$

$$\left(\frac{2E_F}{K_B T} - \frac{(E_c + E_d)}{K_B T}\right) = \ln\frac{N_d}{N_c}$$

$$E_F = \frac{E_c + E_d}{2} + \frac{K_B T}{2}\ \ln\frac{N_d}{N_c} \text{ --------- (5)}$$

Substitute the value of E_F in equ.(1)

$$n = N_c \exp\left(\frac{-E_c}{K_B T} + \frac{E_c + E_d}{2K_B T} + \frac{\ln\frac{N_d}{N_c}}{2}\right)$$

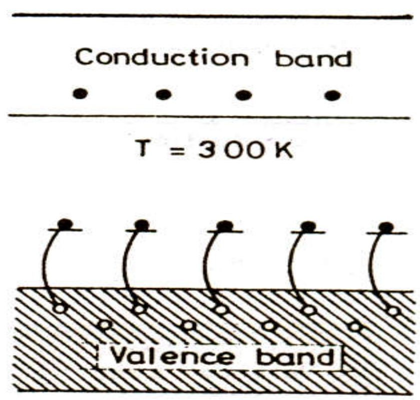
$$n = N_c \exp\left(\frac{-2E_c + E_c + E_d}{2K_B T} + \frac{\ln\frac{N_d}{N_c}}{2}\right)$$

$$n = N_c \exp\left(\frac{E_d - E_c}{2K_B T} + \ln\left(\frac{N_d}{N_c}\right)^{1/2}\right)$$

$$n = N_c \left(\frac{N_d}{N_c}\right)^{1/2} \exp\left(\frac{E_d - E_c}{2K_B T}\right)$$

$$n = \left(N_c N_d\right)^{1/2}\ \exp\left(\frac{E_d - E_c}{2K_B T}\right) \text{ or ----------- (6)}$$

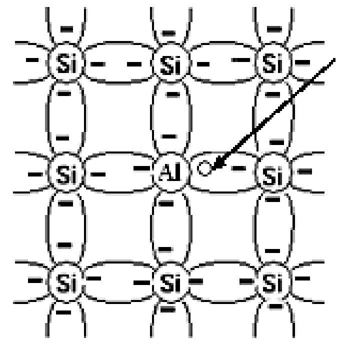
$$n = \left(N_c N_d\right)^{1/2}\ \exp\left(\frac{-\Delta E}{2K_B T}\right) \text{ --------------- (7)}$$



Where $-\Delta E = E_d - E_c$ represents the ionization energy of donors.

P-TYPE SEMICONDUCTOR

When trivalent impurity such as aluminum, boron, gallium or indium is added to pure silicon, it forms 3 covalent bonds with the neighboring 3 silicon atoms while the fourth bond is not completed due to the deficiency of one electron. Thus the trivalent impurity atom has a tendency to accept one electron from neighboring silicon atom to complete the fourth covalent bond. The energy level corresponding to the electron deficiency that is 'hole' is located above the valence bond and is called acceptor level.



In this type of semiconductor majority charge carriers are holes and minority charge carriers are electrons, called p-type semiconductor.

CONDUCTIVITY OF EXTRINSIC SEMICONDUCTORS

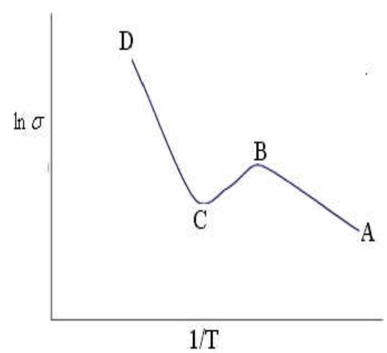
The expression for conductivity for n-type semiconductors is
$\sigma_e = ne\mu_e$ ---------- (1) and

For p-type material is $\sigma_p = ne\mu_h$ --------- (2)

Where μ_e and μ_h are mobilities of electrons and holes.

Under the condition of thermal equilibrium electron and holes are uniformly distributed in semiconductor and the average velocity of charge carriers is zero, no current flows.

Conductivity is temperature dependent as shown in figure.



At low temp the conductivity increases with increase of temperature. This is due to increase in the no. of conduction electrons due to ionization of donor impurities. Conductivity reaches maximum value B in the graph all donors is ionized. Conductivity decreases further increase with temperature. This is due to decrease of mobility because of scattering of electrons from the periodic potential field. A sharp rise in conductivity from C to D is due to large increase in intrinsic conductivity.

DRIFT & DIFFUSION

The net current that flows across semi conducting crystal has two components.

(i) Drift current
(ii) Diffusion current

DRIFT CURRENT

When voltage is applied electrons attracted towards the positive potentials and holes attracted towards the negative potential. This net movement of charge carriers is called drift.

Due to the application of voltage charge carriers attain drift velocity V_d , which is proportional to the electric field E.

$\therefore$ Total current density in semiconductor due to electrons is $J_e = J_{e(drift)} + J_{e(diff.)}$

$$= ne\mu_e E + eD_e \frac{\partial}{\partial x}(\Delta n)$$

$$= (n\mu_e E + D_e \frac{\partial}{\partial x}(\Delta n))\, e \text{ ---------- } (3)$$

Current density due to holes is

$J_h = J_{h(drift)} + J_{h(diff.)}$

$$= pe\mu_h E + (-D_h \frac{\partial}{\partial x}(\Delta p))$$

$$J_h = (p\mu_h E - D_h \frac{\partial}{\partial x}(\Delta p))\, e \text{ ---------- } (4)$$

EINSTEIN'S RELATION

Einstein's relation gives the direct relation between diffusion coefficient and mobility of charge carriers. At equilibrium condition drift current balances and opposite to the diffusion current .

$$\therefore\ ne\mu_e E = -\, eD_e \frac{\partial n}{\partial x} \text{ ---------- } (1)$$

$$ne\mu_e E = -(1/\mu_e)\ eD_e \frac{\partial n}{\partial x} \text{ ---------- } (2)$$

Einstein compared the movement of charge carriers with the gas molecules in a container.
According to Boltzmann's statistics the concentrations of gas molecules can be written as

$$n = C.\exp\left(\frac{-Fx}{K_B T}\right) \text{ where x is distance and F = eE is force acting on the charge carriers}$$

$$\frac{\partial n}{\partial x} = C.\exp\left(\frac{-eEx}{K_B T}\right).\ \left(\frac{-eE}{K_B T}\right) \quad , \quad \frac{\partial n}{\partial x} = n.\left(\frac{-eE}{K_B T}\right) \text{ ----------- } (3)$$

$$F=neE= K_B T\ \frac{\partial n}{\partial x} \text{ ----------- } (4)$$

$$\therefore\ ne\mu_e E = neD_e\left(\frac{eE}{K_B T}\right)$$

$$\frac{D_e}{\mu_e} = \frac{K_B T}{e} \text{ ---------- (2) for electrons} \qquad \frac{D_h}{\mu_h} = \frac{K_B T}{e} \text{ --------- (3) for holes}$$