MODULE 1.2

CARRIER TRANSPORT PHENOMENA

Carrier Transport Phenomenon

- **Carrier drift: mobility, conductivity and velocity saturation**
- **Carrier Diffusion: diffusion current density, total current density**
- **The Einstein relation**

Carrier Transport Phenomenon

- Densities of charged particles are important to understand the electrical properties of a semiconductor material.

- Net flow of the electrons and holes in a semiconductor generate currents. The process by which these charged particles move is called ***transport.***

- Two basic transport mechanisms in a semiconductor crystal are:

•**Drift:**- the movement of charge due to electric fields,
•**Diffusion:**-the flow of charge due to density gradients.

- Temperature gradients in a semiconductor can also lead to carrier movement, but since device size is small, this effect is ignored.

- Carrier transport determines the current-voltage characteristics of semiconductor devices.

- First, semiconductor in equilibrium is discussed

Carrier Drift

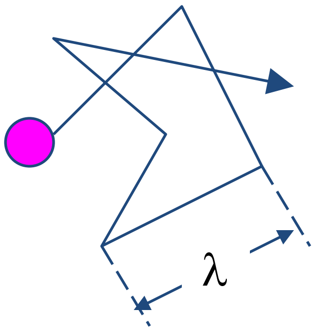
Electric field applied produces a force on electrons and holes, so that they are accelerated.

This net movement of charge due to an electric field is called ***drift, which*** give rise to ***drift current.***

$$\textbf{Av. thermal energy of electron or hole} = \frac{3}{2}k_B T = \frac{1}{2}m^* v_{th}^2$$

$$\textbf{Thermal velocity, } v_{th} = \sqrt{\frac{3k_B T}{m^*}} \cong 2.3\text{x}10^5 \text{ m/sec}$$

The carriers undergo collision with vibrating atoms and charged dopant ions after travelling a distance resulting in scattering of the carriers.



$$\tau_c = \textbf{average time between collisions}$$

$$\lambda = \textbf{mean free path} = v_{th}\tau_c$$

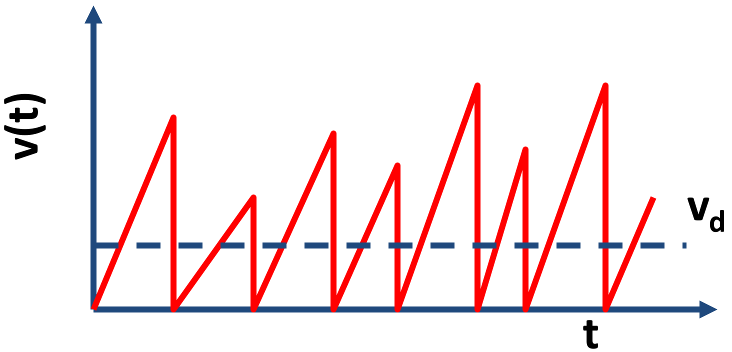
$$\tau_c = 10^{-13} \text{ sec, so } \lambda = 10^5 \text{x} 10^{-13} = 10^{-8}\text{m} = 10\text{nm}$$

Carrier Drift

On application of an electric field, E, and a force, **F = qE/m*** acts on the carrier between collisions.

When the charged particle collides with an atom in the crystal, the particle loses most of its energy. The particle will again begin to accelerate and gain energy until it is again involved in a scattering process. This continues over and over again. Throughout this process, the particle will gain an average drift velocity which, for low electric fields, is directly proportional to the electric field.

$$\mathbf{v(t)} = \pm \frac{\mathbf{q}E}{\mathbf{m_{n,p}}}\mathbf{t}$$



Average time between collision is $\tau_{n,p}$.

Drift velocity, v_d = Average net velocity of carrier due to drift field

For small E,

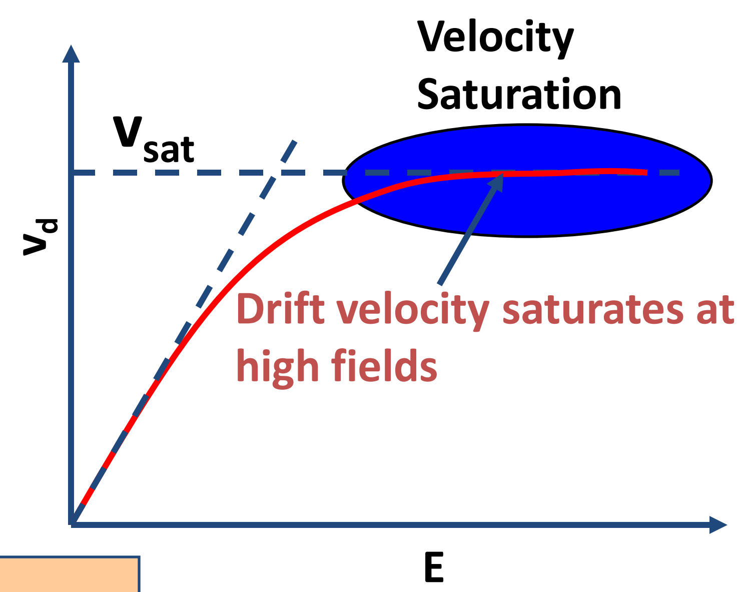
$$\mathbf{v_d} = \pm \frac{\mathbf{q}E}{\mathbf{m_{n,p}}}\tau_{n,p} = \pm \frac{\mathbf{q}\tau_{n,p}}{\mathbf{m_{n,p}}}E$$

Mobility:

For $\mathrm{E} \Rightarrow 0$,

$$v_d = \pm \frac{q\tau_{n,p}}{m_{n,p}} \mathrm{E} = \mu_{n,p}\mathrm{E}$$

$$\mu_{n,p} = \frac{q\tau_{n,p}}{m_{n,p}} = \text{mobility}$$

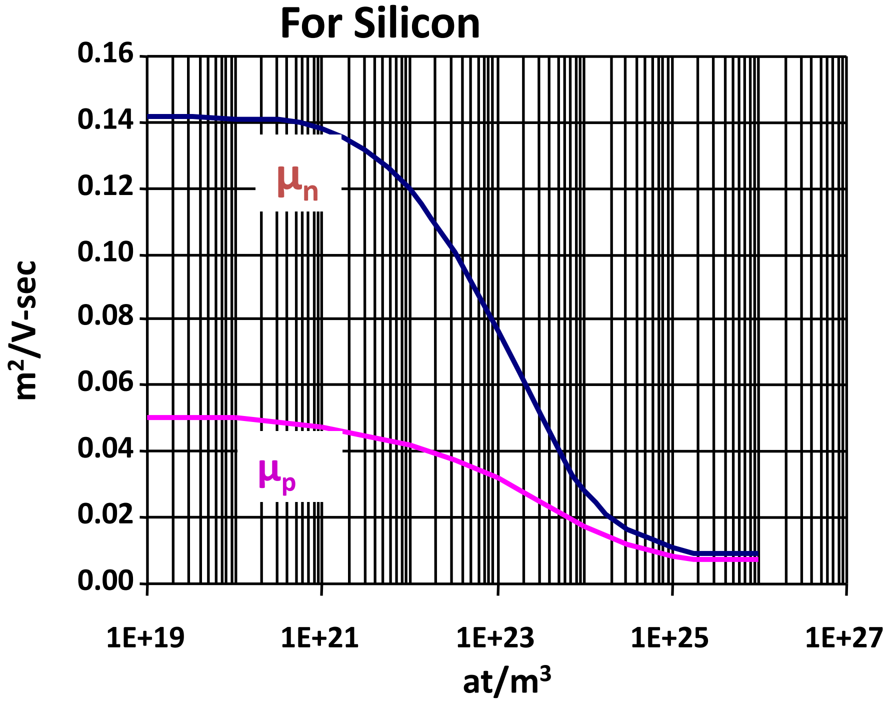


For electrons, $v_{dn} = -\mu_n \mathrm{E}, \quad \mu_n = \frac{q\tau_n}{m_n}$

For holes, $v_{dp} = \mu_p \mathrm{E}, \quad \mu_p = \frac{q\tau_p}{m_p}$

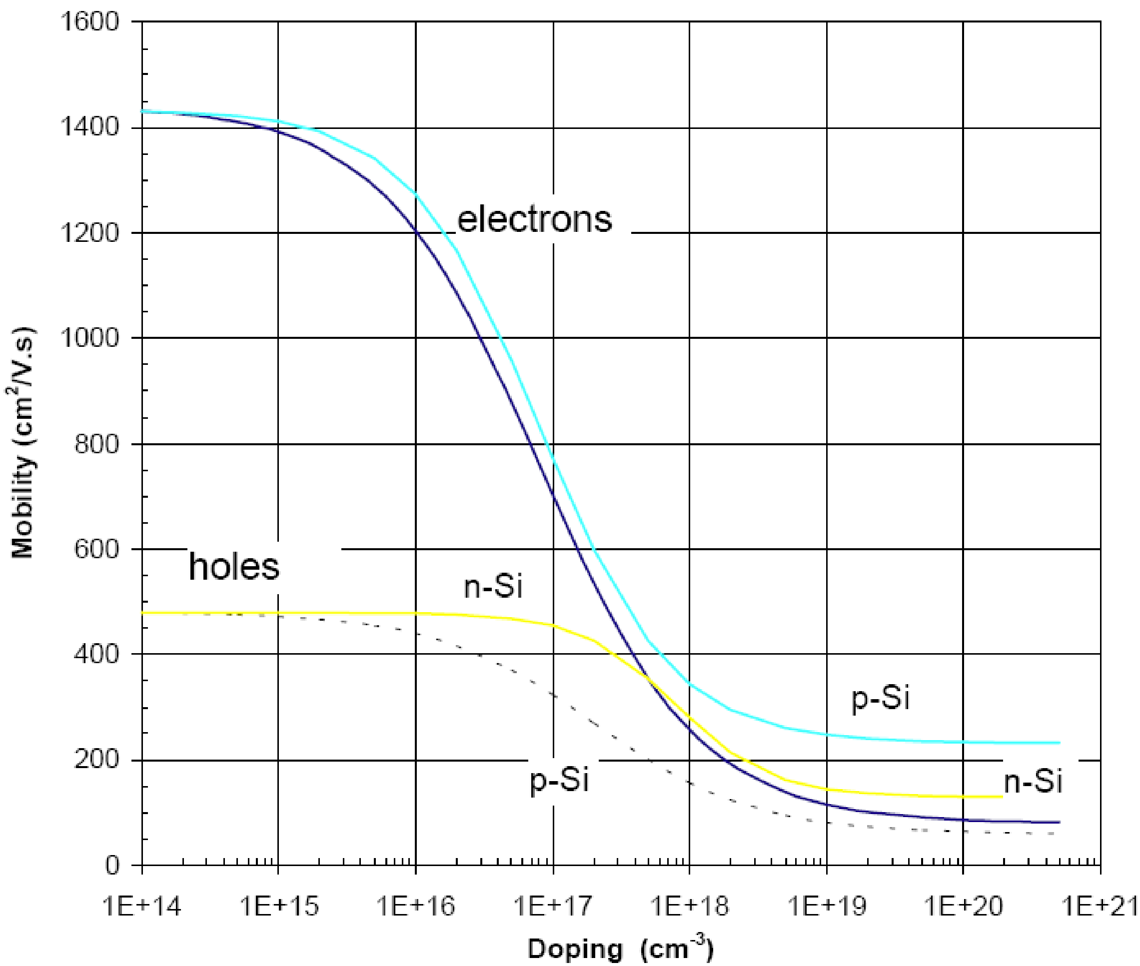
Electron & hole mobilities:

- At low doping levels, the mobility is limited by collision with lattice, i.e., phonons
- At high doping levels, mobility is limited by scattering by dopant ions
- $\mu_n > \mu_p$ for same doping level, since holes have higher effective mass than electrons.



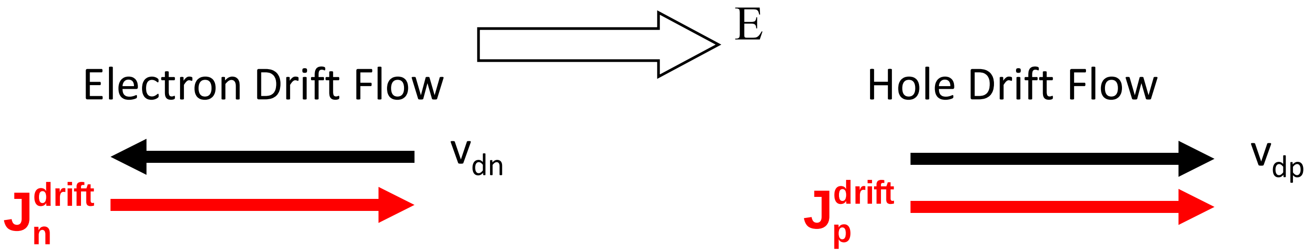
	Ge	Si	GaAs
$\mu_{n,}$, m^2/V-sec (cm^2/V-Sec)	0.39 (3900)	0.14 (1400)	0.85 (8500)
$\mu_{p,}$ m^2/V-sec (cm^2/Vsec)	0.19 (1900)	0.047 (470)	0.04 (400)

Electron & hole mobilities:



Drift Current :

Current due to drift of carriers in presence of an electric field then will be given by:



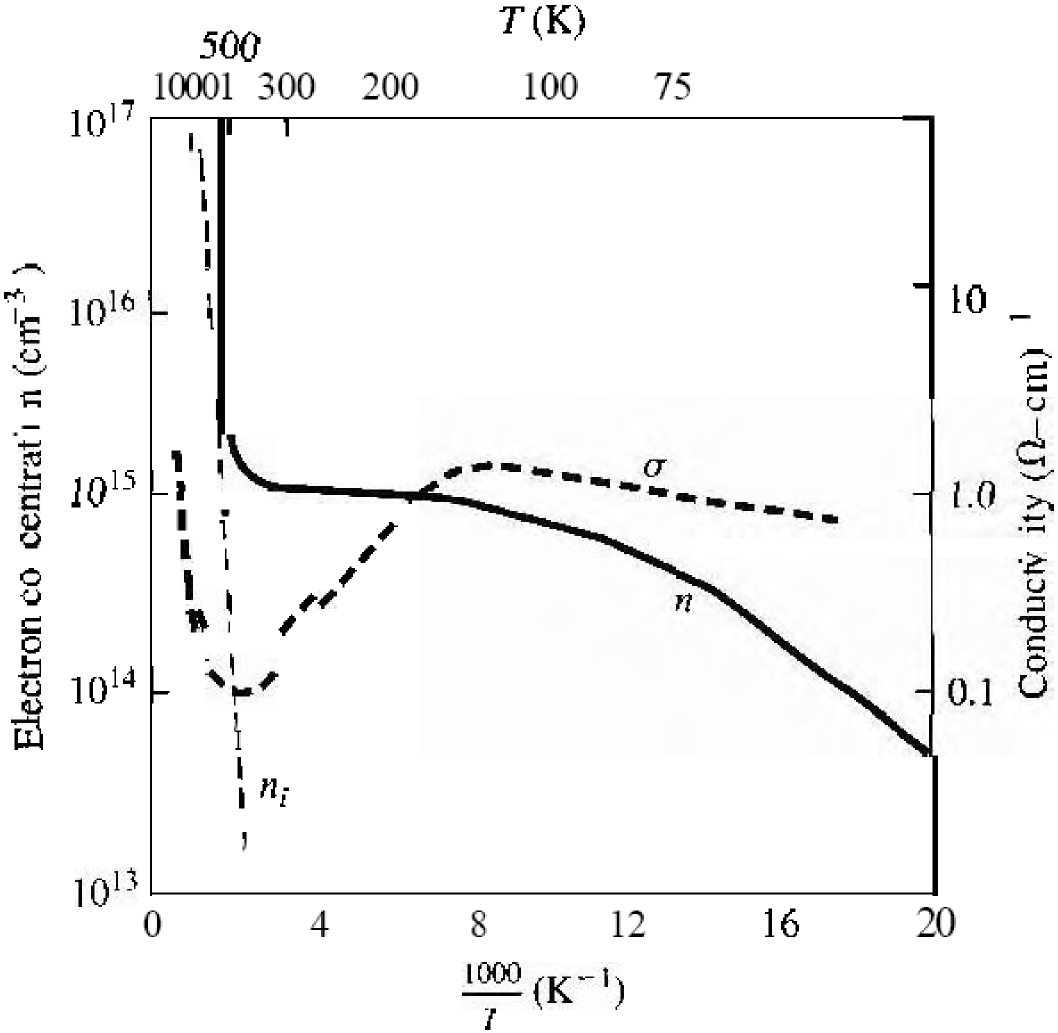
$$\textbf{Electron drift current density} = J_n^{drift} = -qnv_{dn} = qn\mu_n E$$

$$\textbf{Hole drift current density} = J_p^{drift} = +qpv_{dp} = qp\mu_p E$$

$$J^{drift} = J_n^{drift} + J_p^{drift} = q(n\mu_n + p\mu_p)E$$

$$J^{drift} = \sigma E \text{ where } \sigma = \text{conductivity}$$

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

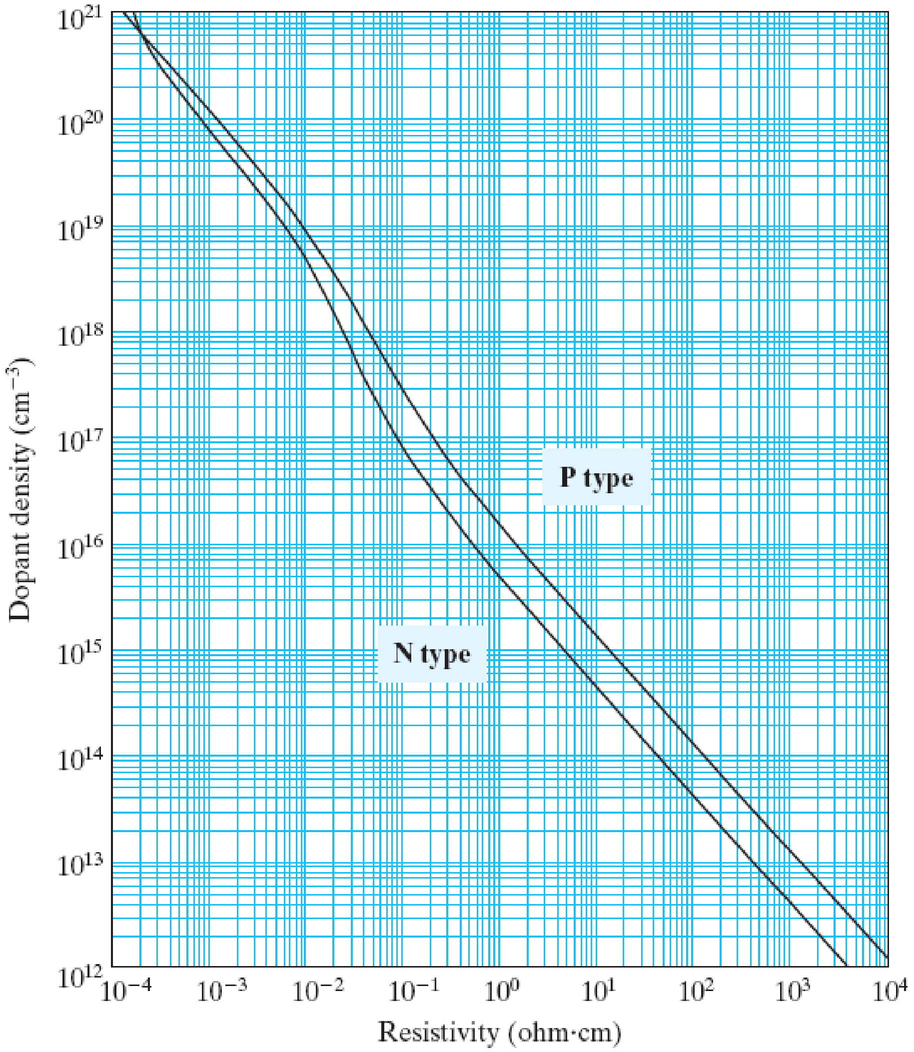


(i) High temp.:-
(intrinsic) carriers are high
'σ' is high

(ii) mid temp.(RT):-
(extrinsic), complete ionisation
Carriers are const.
So 'σ' is const.

(iii) Low temp. :-
(freeze out zone)
Carriers less.
So 'σ' is also less

Resistivity of Silicon :



Scattering Mechanisms:

Mobility of carriers is affected by scattering mechanisms.
Scattering mechanism is of two types – phonon and impurity

[A] Electrons move freely and unperturbed in a perfect periodic potential in a solid.

•But the thermal vibrations cause a disruption of the potential function, resulting in an interaction between the electrons or holes and the vibrating lattice atoms.

•This affect the velocity and mobility of the carriers which is called to as *phonon scattering.*

[B]Impurity atoms are added to the semiconductor to control or alter its characteristics.

•These impurities are ionized at room temperature so that a coulomb interaction exists between the electrons or holes and the ionized impurities.

•This coulomb interaction produces scattering or collisions and also alters the velocity of the charge carrier:- *impurity scattering.*

Scattering Mechanisms:

- Phonon scattering increases with temperature
  τ_p = collision time of carriers due to phonon scattering
  $\tau_p \propto 1/(\text{phonon density x thermal velocity}) \propto 1/(T^*T^{1/2}) \propto T^{-3/2}$

- Impurity scattering increases with concentration of impurity atoms and defects.
- As temp. increases, carriers posses high thermal vel., so easily pass by the impurities

τ_I = coll. time of electron due to impurities and defects $\propto \frac{T^{3/2}}{(N_a + N_d)}$

- Total Scattering effect =

$$\mu_{n,p} = \frac{q\tau_T}{m_{n,p}}$$

$$\frac{1}{\tau_T} = \frac{1}{\tau_P} + \frac{1}{\tau_I} \Rightarrow \frac{1}{\mu_{n,p}} = \frac{1}{\mu_T} + \frac{1}{\mu_I}$$

Mobility vs. Temperature

Mobility is determined by

- Lattice scattering (dominant at high T)

At small dopant conc.,
μ decreases with increasing *T,*
Indicating the dominance of phonon scattering

- Impurity scattering (dominant at low T)

At very high dopant conc.,
and low temperature, impurity
Scattering dominate,
so μ increases with increasing *T*