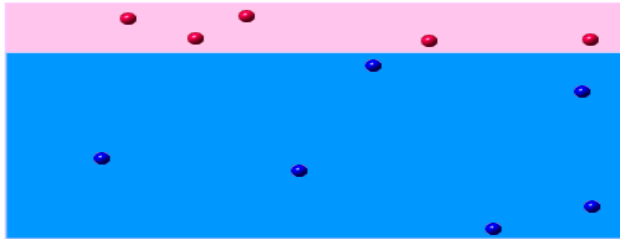


Carrier transport

- Generation and recombination
- Carrier transport
- Carrier drift
 - Mobility
 - Scattering
 - Conductivity and Resistivity
 - Resistivity Measurement: Hall Effect
- Carrier diffusion
 - Diffusion
 - Einstein Relationship

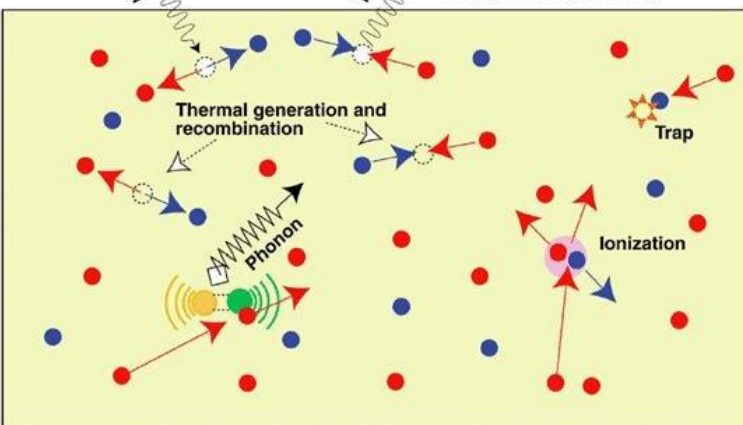
Recombination and generation of carriers

Recombination
vs Collection



Excitation and Relaxation

Photon (absorption) Photon (emission, radiative recombination)



- Three primary types of carrier action occur inside a non-thermal-equilibrium semiconductor
- **Drift:** charged particle motion under the influence of an electric field.
- **Diffusion:** particle motion due to concentration gradient or temperature gradient.
- **Recombination-generation (R-G):** governed by continuity equation

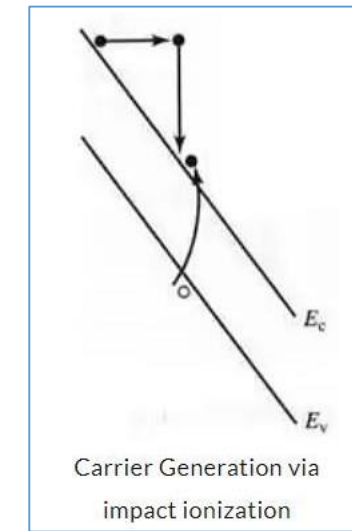
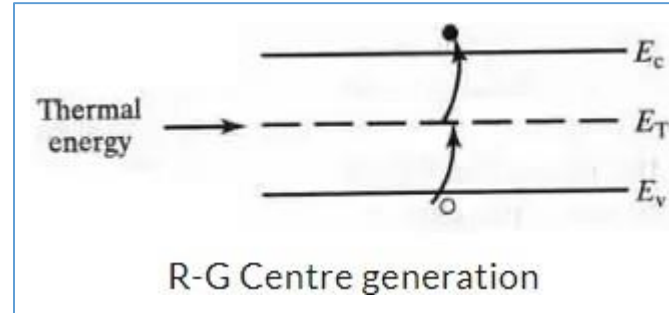
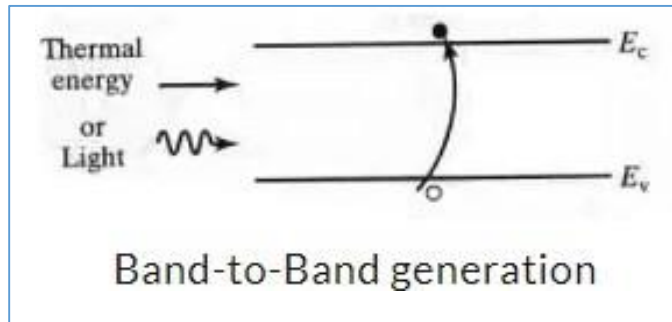
	Generation	Recombination
Radiative process	Photo generation	Radiative recombination
Non-radiative process	Impact Ionization Phonon generation	Auger recombination Phonon recombination

When a semiconductor is in non-equilibrium, then excess carriers may be generated. If in thermal equilibrium, carrier concentration is n_i and in non-equilibrium is n_1 . $n_1 > n_i$

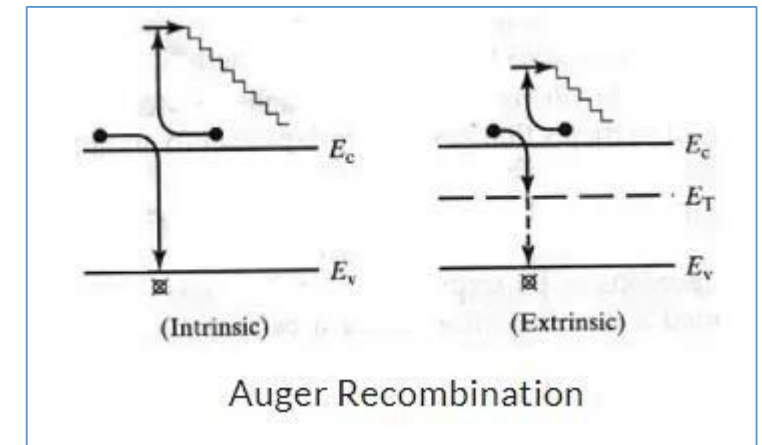
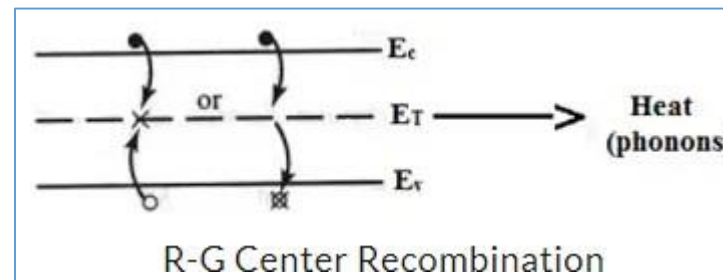
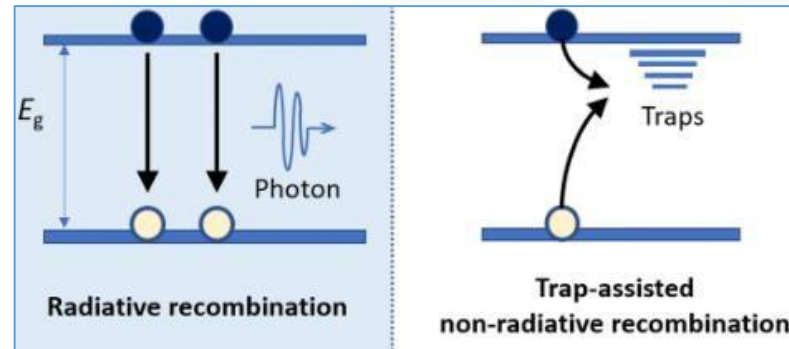
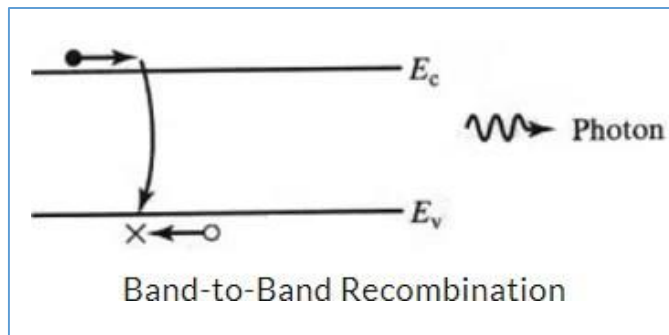
- **Photogeneration** - Light of wavelength falls on a semiconductor and if energy of light is greater than the bandgap of the semiconductor then one electron will jump from valence band to conduction band generating an electron hole pair (EHP).
- **Phonon generation** - when semiconductor is under thermal excitation, lattice vibrations increase which give rise to more phonons resulting in EHP generation by breaking of covalent bonds.
- **Impact ionization** - one energetic carrier will create another charge carrier.

- **Radiative recombination** - electrons from conduction band minimum falls to valence band maximum without changing the momentum and one photon of energy, E_g is emitted. This is seen in GaAs semiconductor.
- **Trap assisted non-radiative recombination** - electron from conduction band minimum comes to a defect level intermediate between E_c and E_v by radiating energy as photons or phonons and then turn from intermediate to valence band
- This is seen in impure semiconductors with defect levels.
- **Auger recombination** - electron and hole recombine but instead of giving energy as photon or phonon, the energy is given to the third free electron in the conduction band.
- Third excited electron comes back to conduction band edge by emitting energy as heat.
- This is seen in heavily doped materials.

EHP Generation processes:

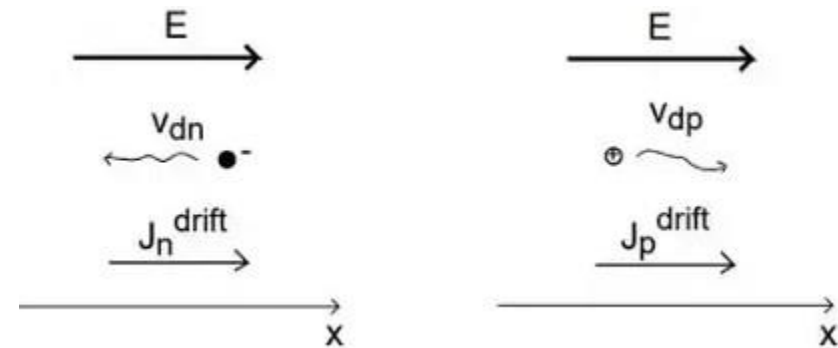
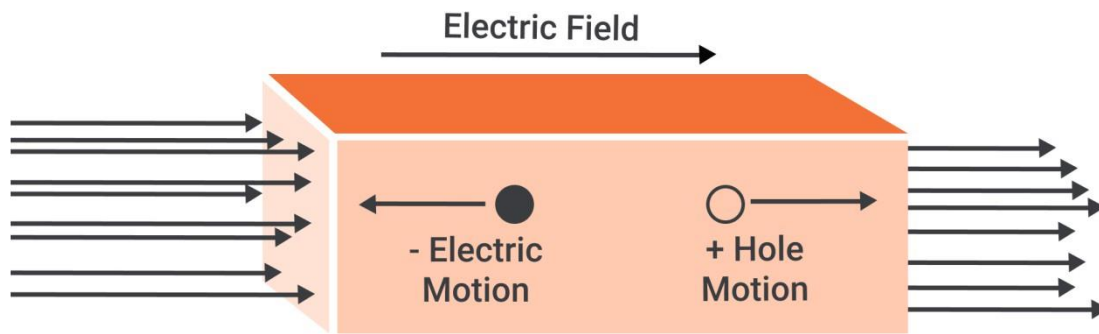


EHP Recombination processes:

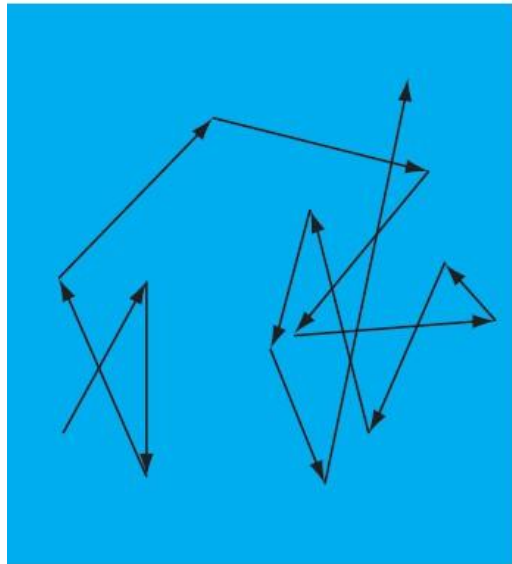


Drift current

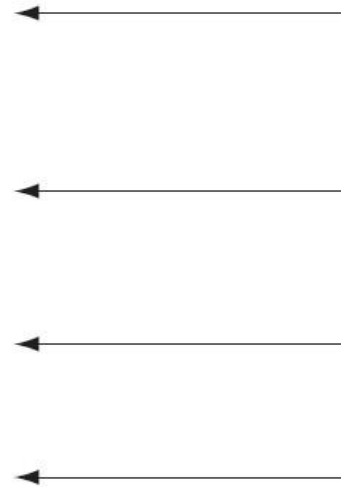
- Drift current arises from the **movement of carriers in response to an applied electric field**. Positive carriers (holes) move in the same direction as the electric field while negative carriers (electrons) move in the opposite direction. The net motion of charged particles generates a drift current that is in the same direction as the applied electric field.
- The drift velocity increases with increasing electric field and contributes to the mobility μ of the carriers. The drift current follows Ohm's law and is mainly influenced by the external field and charge carrier concentration.



When an electric field is applied to a semiconductor, mobile charge carriers will be accelerated by the electrostatic force. This force superimposes on the random motion of electrons and electrons drift in the direction opposite to the electric field resulting in the flow of current.



(a)



$$v_x = -\mu_n \mathcal{E}_x$$

(b)

Figure 3–20

(a) Random thermal motion of an electron in a solid; (b) well-directed drift velocity with an applied electric field.

$-x$ -direction (Fig. 3–20b). If p_x is the x -component of the total momentum of the group, the force of the field on the n electrons/cm³ is

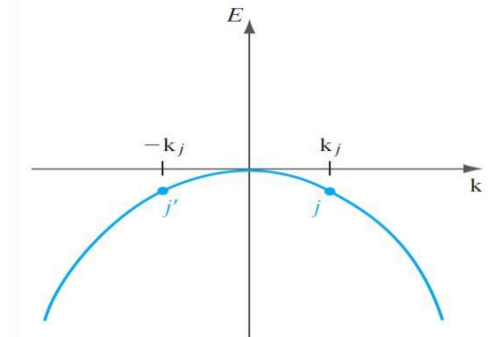
$$-nq\mathcal{E}_x = \left. \frac{dp_x}{dt} \right|_{\text{field}} \quad (3-29)$$

oppositely directed velocities. With N electrons/cm³ in the band we express the current density using a sum over all of the electron velocities, and including the charge $-q$ on each electron. In a unit volume,

$$J = (-q) \sum_i^N v_i = 0 \quad (\text{filled band}) \quad (3-2a)$$

Now if we create a hole by removing the j th electron, the net current density in the valence band involves the sum over all velocities, minus the contribution of the electron we have removed:

$$J = (-q) \sum_i^N v_i - (-q)v_j \quad (j\text{th electron missing})$$



Using Eq. (3–36) for the average velocity, we obtain

$$J_x = \frac{nq^2\bar{t}}{m_n^*}\mathcal{E}_x \quad (3-38)$$

Thus the current density is proportional to the electric field, as we expect from Ohm's law:

$$J_x = \sigma\mathcal{E}_x, \quad \text{where } \sigma \equiv \frac{nq^2\bar{t}}{m_n^*} \quad (3-39)$$

The conductivity $\sigma(\Omega\text{-cm})^{-1}$ can be written

$$\sigma = qn\mu_n, \quad \text{where } \mu_n \equiv \frac{q\bar{t}}{m_n^*} \quad (3-40a)$$

The quantity μ_n , called the *electron mobility*, describes the ease with which electrons drift in the material. Mobility is a very important quantity in characterizing semiconductor materials and in device development.

The mobility defined in Eq. (3–40a) can be expressed as the average particle drift velocity per unit electric field. Comparing Eqs. (3–36) and (3–40a), we have

$$\mu_n = -\frac{\langle v_x \rangle}{\mathcal{E}_x} \quad (3-41)$$

The unit of mobility is $(\text{cm/s})/(\text{V/cm}) = \text{cm}^2/\text{V-s}$, as Eq. (3–41) suggests. The minus sign in the definition results in a positive value of mobility, since electrons drift opposite to the field.

The current density can be written in terms of mobility as

$$J_x = qn\mu_n\mathcal{E}_x \quad (3-42)$$

This derivation has been based on the assumption that the current is carried primarily by electrons. For hole conduction we change

When an electric field is applied to the crystal, electrons and holes experience a net acceleration in a direction in addition to its random motion. As the charged particle accelerates, the velocity increases and then it suddenly collides with a vibrating atom and loses the gained velocity. The particle will again begin to accelerate and gain energy until it is again involved in a scattering process. Throughout this process the particle will gain an average **drift velocity**.

Drift Current Density:

If we have a positive volume charge density ρ moving with an average drift velocity v_d , the drift current density,

$$j = \frac{I}{A} \quad \text{Current density} \quad J_{drift} = \rho v_d \quad C/cm^2-s \quad \text{or} \quad \text{Amp}/cm^2$$

$$\text{Charge Density } \rho = -en \quad \text{or} \quad = ep \quad \rho \cong \frac{1}{qp\mu_p}$$

- Mobility is directly related to the mean free time between collisions, which is in turn determined by scattering.
- The two basic types of scattering mechanisms that influence electron and hole mobility are lattice scattering and impurity scattering.
- In **lattice scattering** a carrier moving through the crystal is scattered by a vibration of the lattice, resulting from the temperature.
- The **frequency of such scattering events increases as the temperature increases**, since the thermal agitation of the lattice becomes greater.
- Scattering from crystal defects such as ionized impurities becomes the dominant mechanism at low temperatures.
- **Impurity scattering** events cause a **decrease in mobility with decreasing temperature**

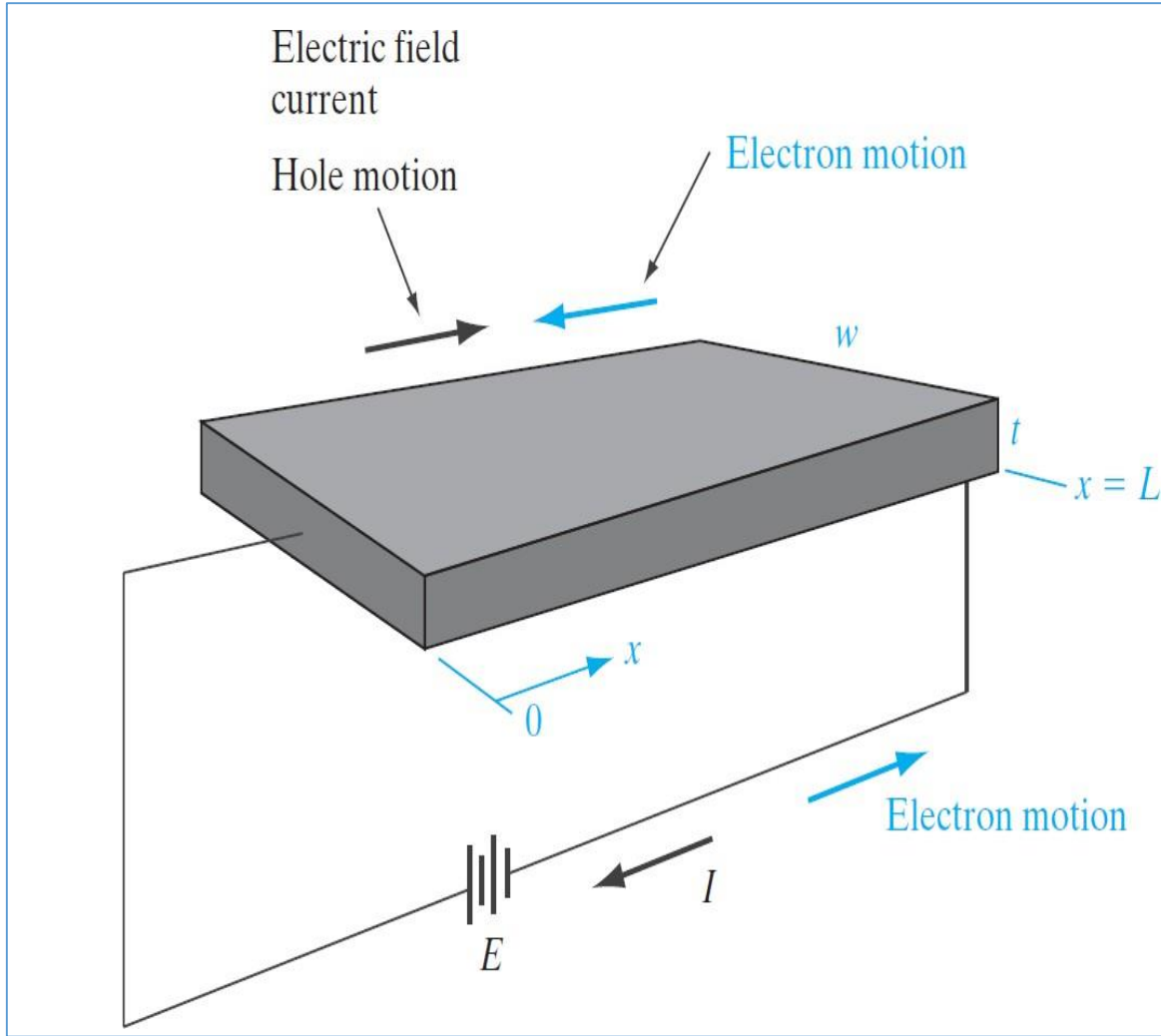
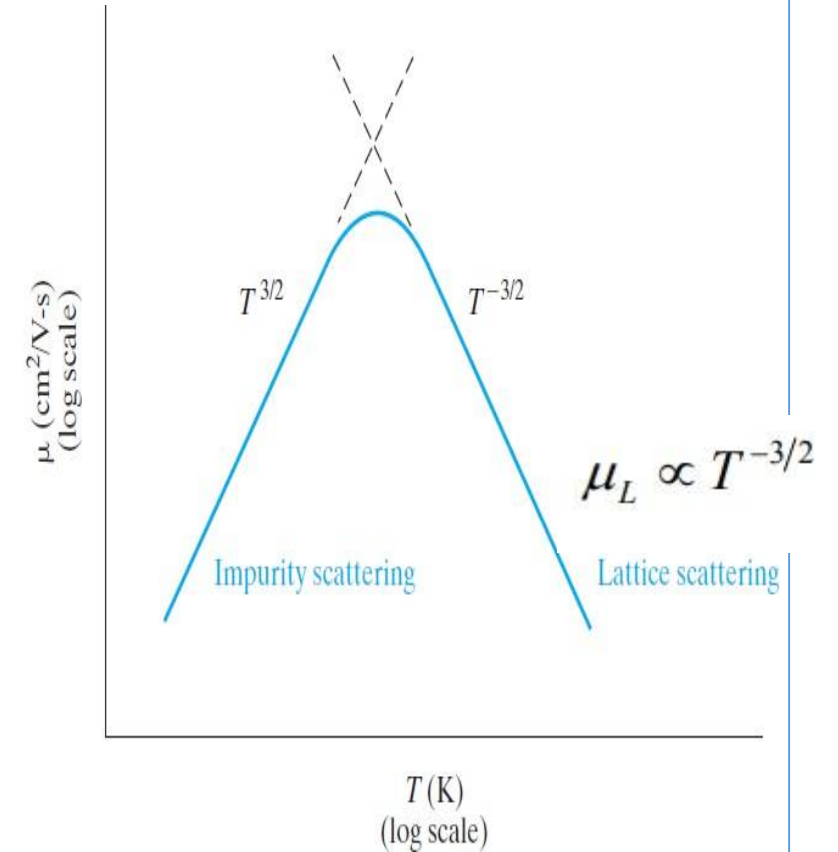


Figure 3-22
Approximate temperature dependence of mobility with both lattice and impurity scattering.



$$\mu_I \propto \frac{T^{3/2}}{N_I}$$

$$N_I = N_d^+ + N_a^-$$

N_I is concentration of the ionized carries

Lattice scattering effects



Lattice vibration causes a local volume change and hence lattice constant change.

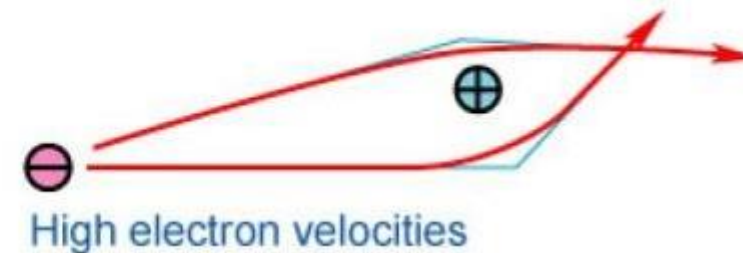
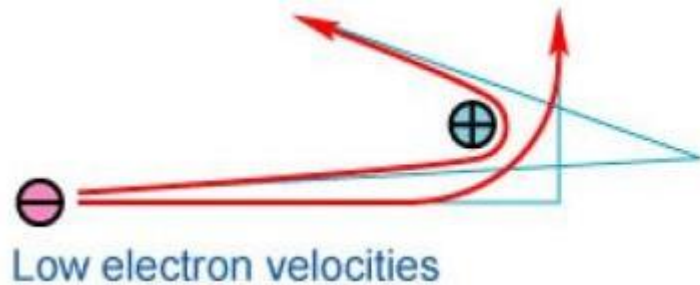


Bandgap generally widens with a smaller lattice constant.



Disruption of valence and conduction band edges scatters the carriers.

Impurity scattering effects



Hall effect

Mathematical expression for the Hall voltage is given by

$$V_H = \frac{I B}{q n d}$$

Where,

V_H = Hall voltage

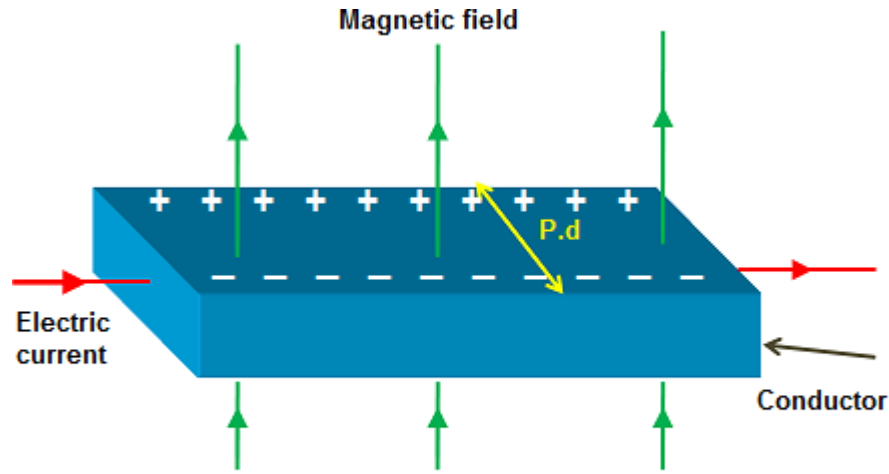
I = current flowing through the material

B = magnetic field strength

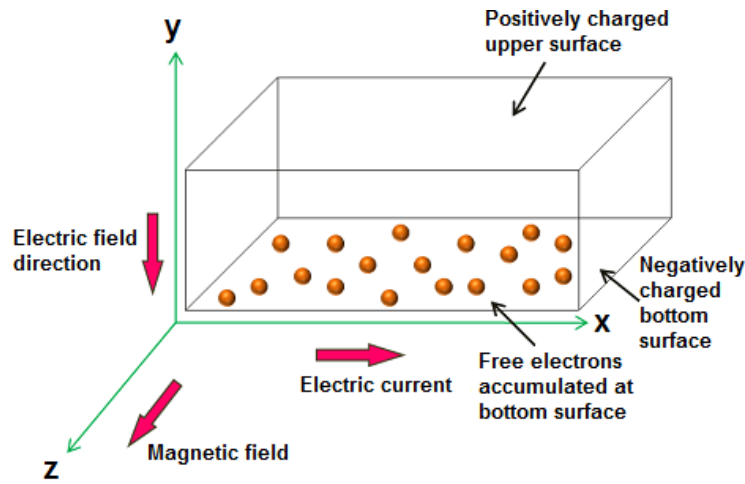
q = charge

n = number of mobile charge carriers per unit volume

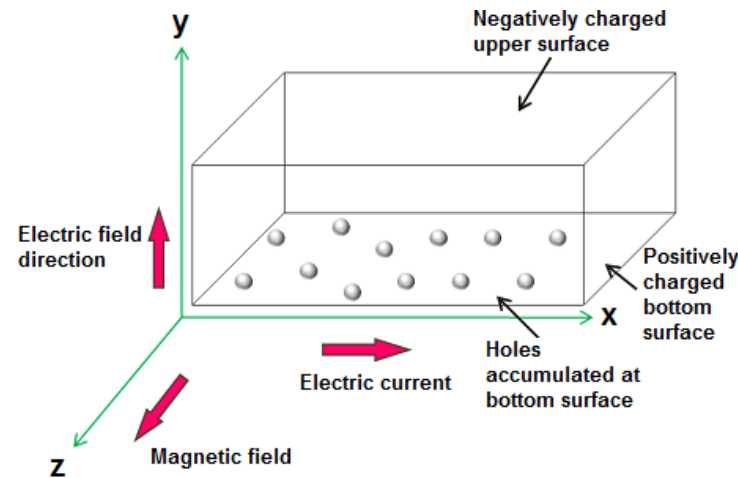
d = thickness of the material



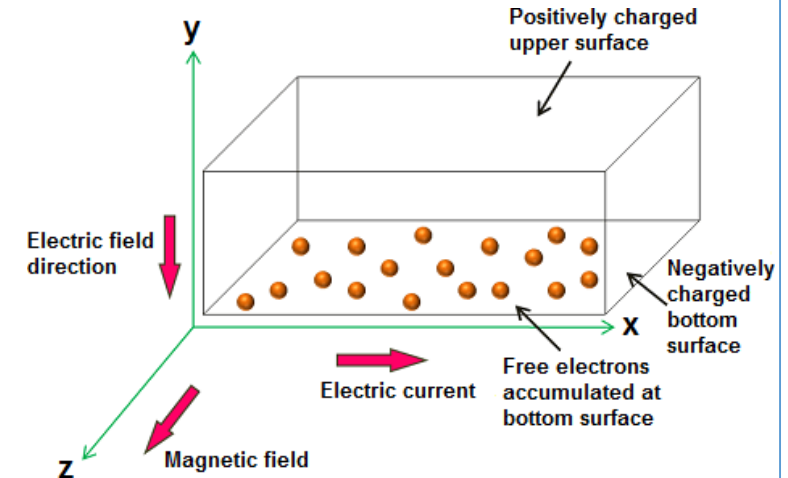
P.d = Potential difference



Hall Effect in conductor



Hall Effect in P-type semiconductor



Hall Effect in N-type semiconductor

Hall effect

For p-type material: V_H will be +ve

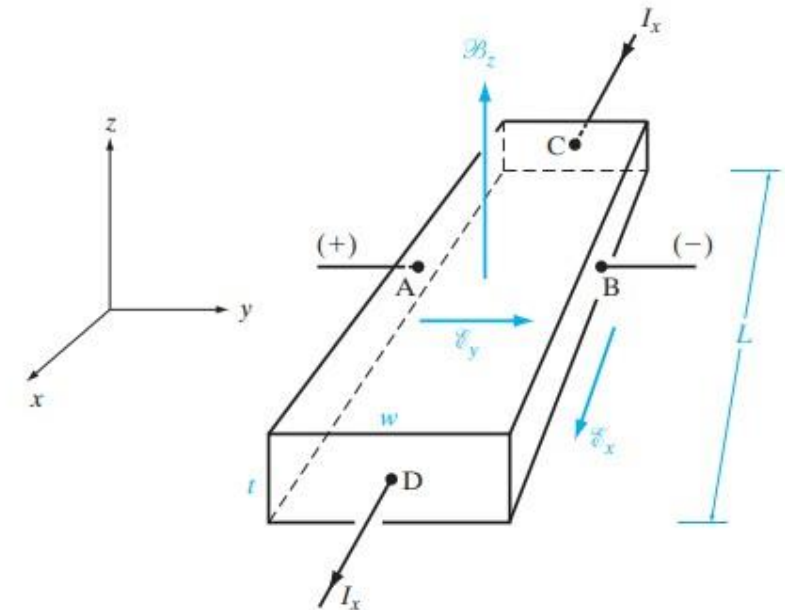
$$v_x = \frac{J_x}{ep} = \frac{I_x}{(ep)(Wd)} \rightarrow V_H = \frac{I_x B_z}{epd} \rightarrow \boxed{p = \frac{I_x B_z}{edV_H}}$$

$$\mathbf{F} = q(\mathcal{E} + \mathbf{v} \times \mathcal{B})$$

(3-46)

For n-type material: V_H will be -ve

$$V_H = -\frac{I_x B_z}{ned} \rightarrow \boxed{n = -\frac{I_x B_z}{edV_H}}$$



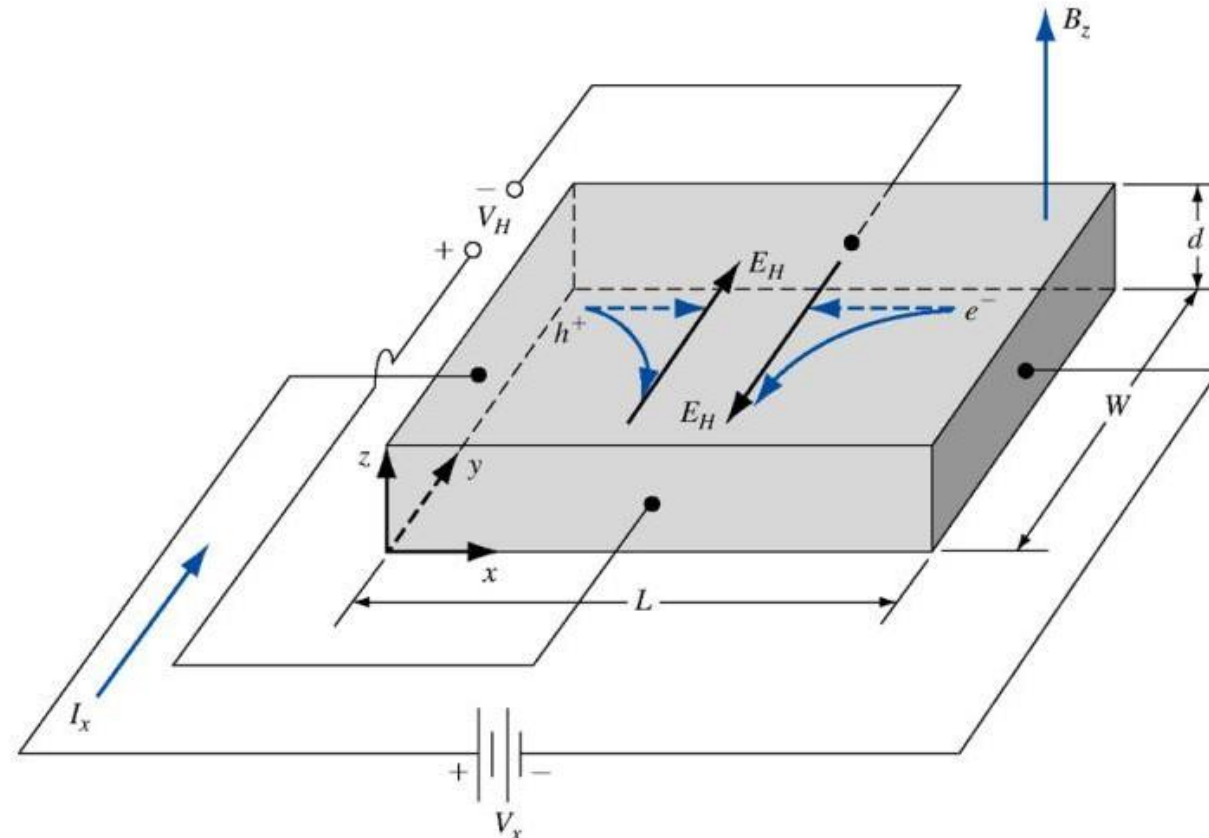
Carriers experience a force, $F_y = ev_x \times B_z$

$$eE_H = ev_x B_z$$

$$V_H = E_H W$$

$$p = \frac{I_x B_z}{eV_H d}$$

$$\mu_p = \frac{I_x L}{epV_x W d}$$



$$R_H \equiv \frac{1}{qp} \quad (20)$$

The Hall field \mathcal{E}_y is proportional to the product of the current density and the magnetic field. The proportionality constant R_H is the *Hall coefficient*. A similar result can be obtained for an *n*-type semiconductor, except that the Hall coefficient is negative:

Derivation of Hall voltage

$$F = qv \times B$$

$$F = q[E + v \times B] = 0$$

$$qE_y = qv_x B_z$$

$$V_H = +E_H W$$

$$V_H = v_x W B_z$$

$$v_{dx} = \frac{J_x}{ep} = \frac{I_x}{(ep)(Wd)}$$

$$V_H = \frac{I_x B_z}{epd}$$

$$p = \frac{I_x B_z}{edV_H}$$

$$V_H = -\frac{I_x B_z}{ned}$$

$$n = -\frac{I_x B_z}{edV_H}$$

Hole and electron mobility equations

Once the majority carrier concentration has been determined, we can calculate the low-field majority carrier mobility. For a p-type semiconductor, we can write

$$J_x = ep\mu_p E_x \quad (5.57)$$

The current density and electric field can be converted to current and voltage so that Equation (5.57) becomes

$$\frac{I_x}{Wd} = \frac{ep\mu_p V_x}{L} \quad (5.58)$$

The hole mobility is then given by

$$\mu_p = \frac{I_x L}{epV_x Wd} \quad (5.59)$$

Similarly for an n-type semiconductor, the low-field electron mobility is determined from

$$\mu_n = \frac{I_x L}{enV_x Wd} \quad (5.60)$$

Objective: Determine the majority carrier concentration and mobility, given Hall effect parameters.

Consider the geometry shown in Figure 5.13. Let $L = 10^{-1}$ cm, $W = 10^{-2}$ cm, and $d = 10^{-3}$ cm. Also assume that $I_x = 1.0$ mA, $V_x = 12.5$ V, $B_z = 500$ gauss = 5×10^{-2} tesla, and $V_H = -6.25$ mV.

$$n = -\frac{I_x B_z}{edV_H}$$

$$5 \times 10^{21} \text{ m}^{-3}$$

$$\mu_n = \frac{I_x L}{enV_x Wd}$$

$$0.10 \text{ m}^2/\text{V-s}$$

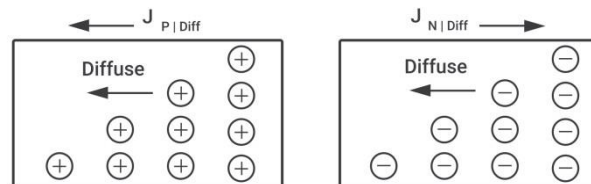
A p-type silicon sample with the geometry shown in Figure 5.13 has parameters $L = 0.2$ cm, $W = 10^{-2}$ cm, and $d = 8 \times 10^{-4}$ cm. The semiconductor parameters are $p = 10^{16}$ cm $^{-3}$ and $\mu_p = 320$ cm 2 /V-s. For $V_x = 10$ V and $B_z = 500$ gauss = 5×10^{-2} tesla, determine I_x and V_H .

$$\frac{I_x}{Wd} = \frac{ep\mu_p V_x}{L} \qquad V_H = \frac{I_x B_z}{epd}$$

Solution: $I_x = 0.2048$ mA and $V_H = 0.8$ mV

Diffusion current

- The **movement of charge carriers from higher concentration to lower concentration** generates diffusion current.
- This occurs when a semiconductor is doped non-uniformly then there is a non-uniform distribution of carriers or a concentration gradient.
- This process does not require an external electric field and is primarily dependent on the repulsive forces between carriers of the same charge that are highly concentrated in an area. The repulsive forces will drive the diffusion of carriers leading to a change in concentrations and eventually a uniform distribution.
- The initial carrier concentrations also determine the direction of the diffusion current—the current moves to the direction where there is initially a higher concentration of electrons or a lower concentration of holes. Quite simply, the current moves in the same direction as the movement of holes and opposite to that of electrons.
- The diffusion current is proportional to the concentration gradient or how non-uniformly the carriers were initially distributed. Since the carriers are diffusing from areas of higher concentration to areas of lower concentration, $+q$ is assigned for electrons and $-q$ is assigned for holes in the equation for the current density.



Equations for diffusion currents

$$J_n(\text{diff.}) = -(-q)D_n \frac{dn(x)}{dx} = +qD_n \frac{dn(x)}{dx}$$

$$J_p(\text{diff.}) = -(+q)D_p \frac{dp(x)}{dx} = -qD_p \frac{dp(x)}{dx}$$

Hole diffusion current

$$J_{px,dif} = -eD_p \frac{dp}{dx} \quad D_p: \text{hole diffusion coefficient (m}^2/\text{s)}$$

Electron diffusion current

$$J_{nx,dif} = eD_n \frac{dn}{dx} \quad D_n: \text{electron diffusion coefficient (m}^2/\text{s)}$$

Total diffusion current

$$J_{dif} = e(D_n \frac{dn}{dx} - D_p \frac{dp}{dx})$$

- The **diffusion current** crossing a unit area (the current density) is the particle flux density multiplied by the charge of the carrier:

$$D = v_{th} \ell$$

Where v_{th} is the thermal velocity and ℓ is the mean free path of the carrier

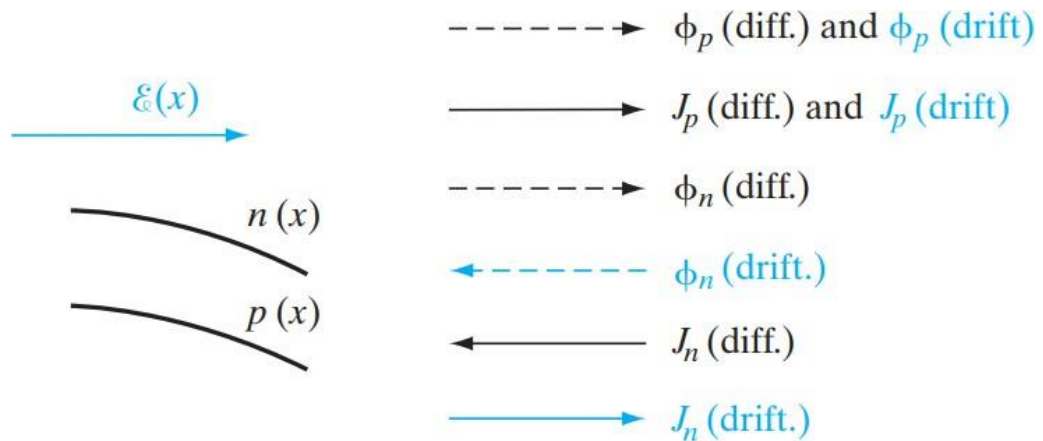
Einstein relation

$$J_n(x) = q\mu_n n(x)\mathcal{E}(x) + qD_n \frac{dn(x)}{dx}$$

drift

diffusion

$$J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p \frac{dp(x)}{dx}$$



- If an electric field is present in addition to the carrier gradient, the current densities will each have a drift component and a diffusion component.
- An electric field is assumed to be in the x -direction, along with carrier distributions $n(x)$ and $p(x)$ which decrease with increasing x and diffusion takes place in the $+x$ -direction.
- The resulting electron and hole diffusion currents $[J_n(\text{diff.})$ and $J_p(\text{diff.})]$ are in opposite directions.
- Holes drift in the direction of the electric field $[\phi_p(\text{drift})]$, whereas electrons drift in the opposite direction because of their negative charge.
- The resulting drift current is in the $+x$ -direction in each case.

- The electrostatic potential $V(x)$ varies in the opposite direction, since it is defined in terms of positive charges and is therefore related to the electron potential energy $E(x)$ displayed in the figure by $V(x) = E(x)/(-q)$

$$\mathcal{E}(x) = -\frac{dV(x)}{dx}$$

$$\mathcal{E}(x) = -\frac{dV(x)}{dx} = -\frac{d}{dx}\left[\frac{E_i}{(-q)}\right] = \frac{1}{q} \frac{dE_i}{dx}$$

At equilibrium, no net current flows in a semiconductor. Thus any fluctuation which would begin a diffusion current also sets up an electric field which redistributes carriers by drift.

$$J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p \frac{dp(x)}{dx}$$

So assume $J_p(x)=0$, then find $E(x)$

$$\mathcal{E}(x) = \frac{D_p}{\mu_p} \frac{1}{p(x)} \frac{dp(x)}{dx}$$

We know that $p_0 = n_i e^{(E_i - E_F)/kT}$

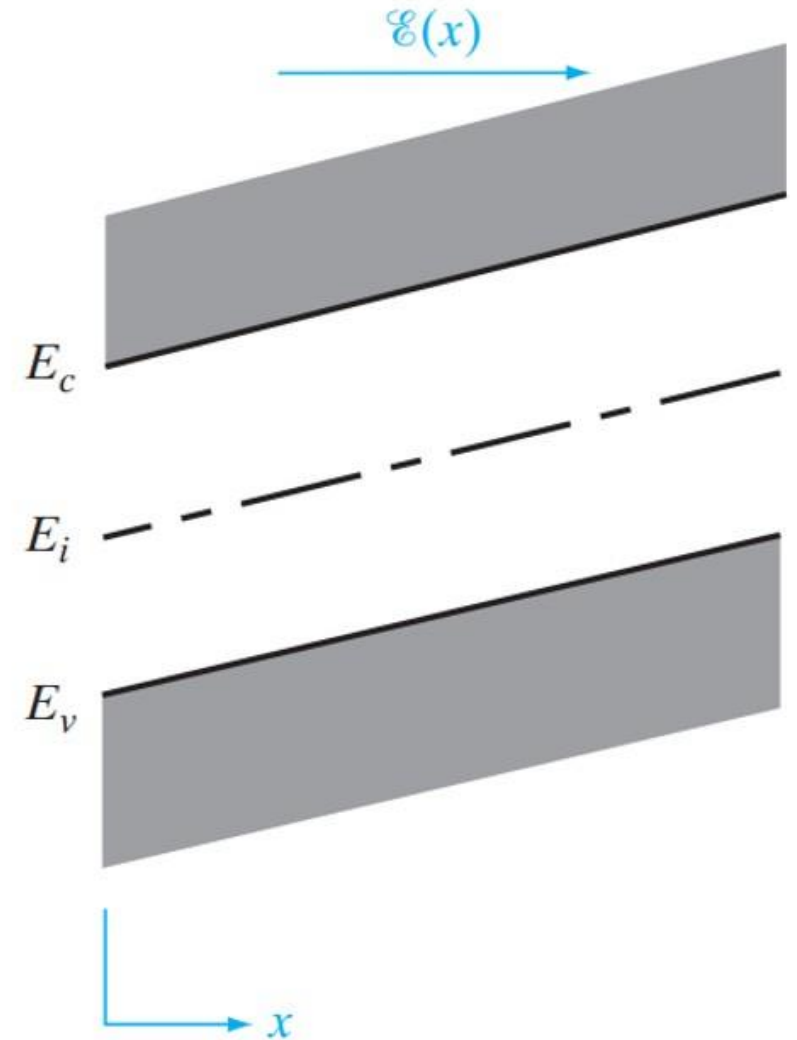
Upon substituting the above equation for $p(x)$, we get

$$\mathcal{E}(x) = \frac{D_p}{\mu_p} \frac{1}{kT} \left(\frac{dE_i}{dx} - \frac{dE_F}{dx} \right)$$

The equilibrium Fermi level does not vary with x ,

$$\text{We know that } \mathcal{E}(x) = \frac{1}{q} \frac{dE_i}{dx}$$

$$\boxed{\frac{D}{\mu} = \frac{kT}{q}}$$



- This result is obtained for either carrier type. This important equation is called the **Einstein relation**. It allows us to calculate either D or μ from a measurement of the other.
- An important result of the balance of drift and diffusion at equilibrium is that **built-in fields** accompany gradients in E_i .
- Such gradients in the bands at equilibrium (E_F constant) can arise when the band gap varies due to changes in alloy composition.
- Built-in fields result from **doping gradients**.
- Carrier diffusivity is related to mobility by the thermal voltage kT/q (Einstein relation)

- The net flow of electrons and holes will generate
- The process by which these charged particles move is called
- Two basic mechanisms:
 - Drift - movement of charges due to electric field
 - Diffusion - flow of charges due to density gradients
 - In some situations, temperature gradients also induce carrier movement
- Carrier transport is the foundation for studying the current-voltage characteristics of the semiconductor devices.

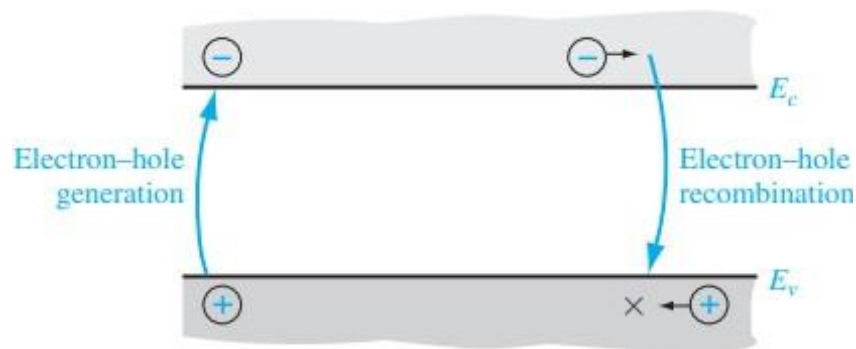


Figure 6.1 | Electron-hole generation and recombination.

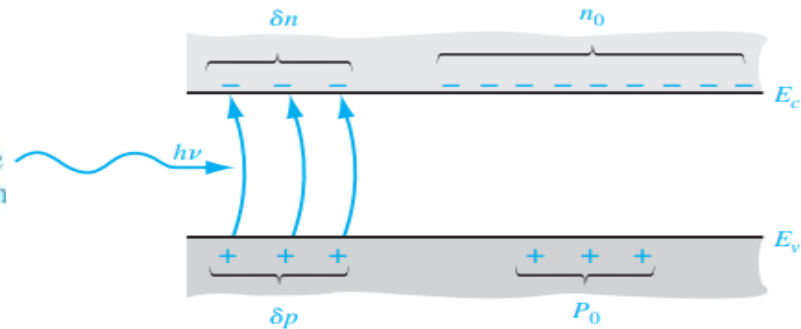


Figure 6.2 | Creation of excess electron and hole densities by photons.

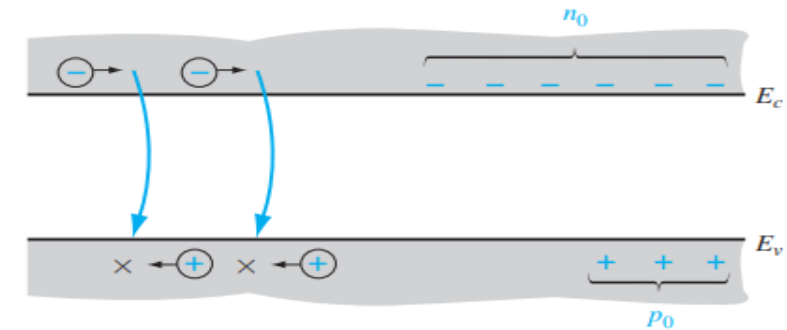


Figure 6.3 | Recombination of excess carriers reestablishing thermal equilibrium.

Non equilibrium carrier concentrations

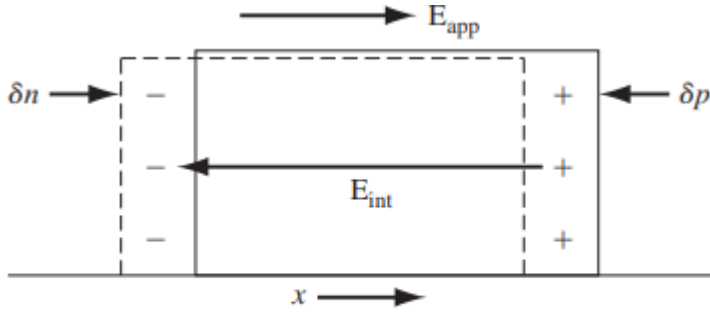


Figure 6.5 | The creation of an internal electric field as excess electrons and holes *tend* to separate.

- Excess electrons and a pulse of excess holes are created at a particular point in a semiconductor with an applied electric field.
- The excess holes and electrons will tend to drift in opposite directions.
- However, because the electrons and holes are charged particles, any separation will induce an internal electric field between the two sets of particles.
- This internal electric field will create a force attracting the electrons and holes back toward each other
- The negatively charged electrons and positively charged holes then will drift or diffuse together with a single effective mobility or diffusion coefficient. This phenomenon is called **ambipolar diffusion or ambipolar transport**.

Quasi fermi energy level

If excess carriers are created in a semiconductor, we are no longer in thermal equilibrium and the Fermi energy is strictly no longer defined. However, we may define a quasi-Fermi level for electrons and a quasi-Fermi level for holes that apply for nonequilibrium. If δn and δp are the excess electron and hole concentrations, respectively, we may write

$$n_0 + \delta n = n_i \exp \left(\frac{E_{Fn} - E_{Fi}}{kT} \right) \quad (6.85a)$$

$$p_0 + \delta p = n_i \exp \left(\frac{E_{Fi} - E_{Fp}}{kT} \right) \quad (6.85b)$$

where E_{Fn} and E_{Fp} are the quasi-Fermi energy levels for electrons and holes, respectively. The total electron concentration and the total hole concentration are functions of the quasi-Fermi levels.

Thus, the processes of electron drift and diffusion are summed up by the spatial variation of the quasi-Fermi level. The same derivation can be made for holes, and we can write the current due to drift and diffusion in the form of a *modified Ohm's law*

$$J_n(x) = q\mu_n n(x) \frac{d(F_n/q)}{dx} = \sigma_n(x) \frac{d(F_n/q)}{dx} \quad (4-52a)$$

$$J_p(x) = q\mu_p p(x) \frac{d(F_p/q)}{dx} = \sigma_p(x) \frac{d(F_p/q)}{dx} \quad (4-52b)$$

Degenerate semiconductors

- As the donor concentration further increases, the band of donor states widens and may overlap the bottom of the conduction band. This overlap occurs when the donor concentration becomes comparable with the effective density of states.
- When the concentration of electrons in the conduction band exceeds the density of states N_c , the Fermi energy lies within the conduction band. This type of semiconductor is called a **degenerate n-type semiconductor**.
- As the acceptor doping concentration increases in a p-type semiconductor, the discrete acceptor energy states will split into a band of energies and may overlap the top of the valence band. The Fermi energy will lie in the valence band when the concentration of holes exceeds the density of states N_v . This type of semiconductor is called a **degenerate p-type semiconductor**.

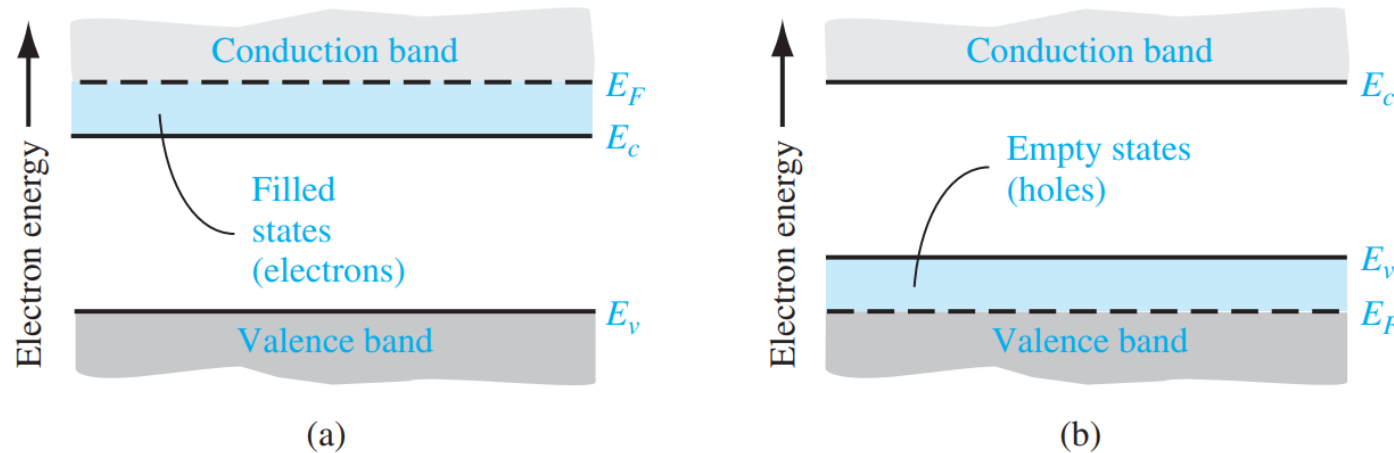


Figure 4.11 | Simplified energy-band diagrams for degenerately doped (a) n-type and (b) p-type semiconductors.

Compensate semiconductors

- Compensated semiconductor is one that contains both donor and acceptor impurity atoms in the same region.
- A compensated semiconductor can be formed, for example, by diffusing acceptor impurities into an n-type material or by diffusing donor impurities into a p-type material.
- An n-type compensated semiconductor occurs when $N_d > N_a$, and a p-type compensated semiconductor occurs when $N_a > N_d$.
- If $N_a = N_d$, we have a completely compensated semiconductor that has, as we will show, the characteristics of an intrinsic material.

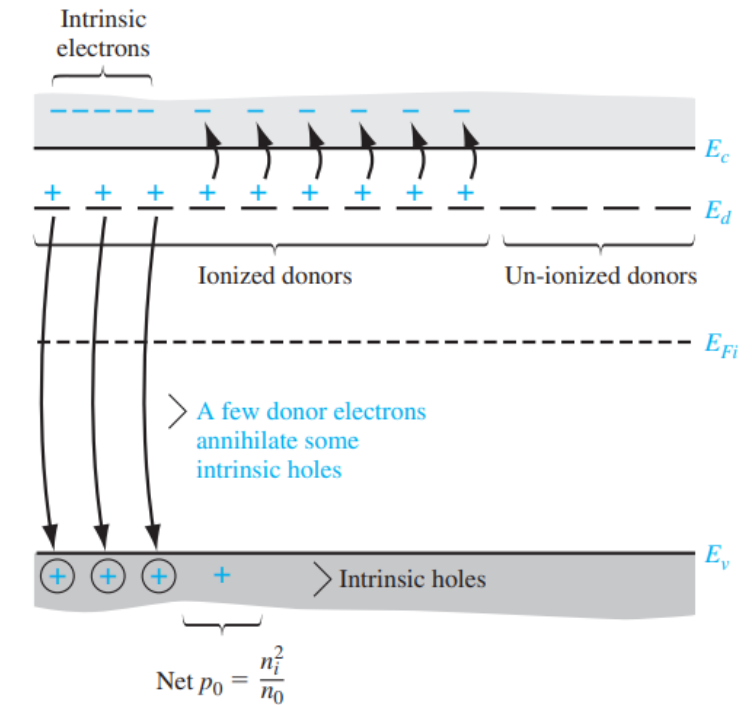
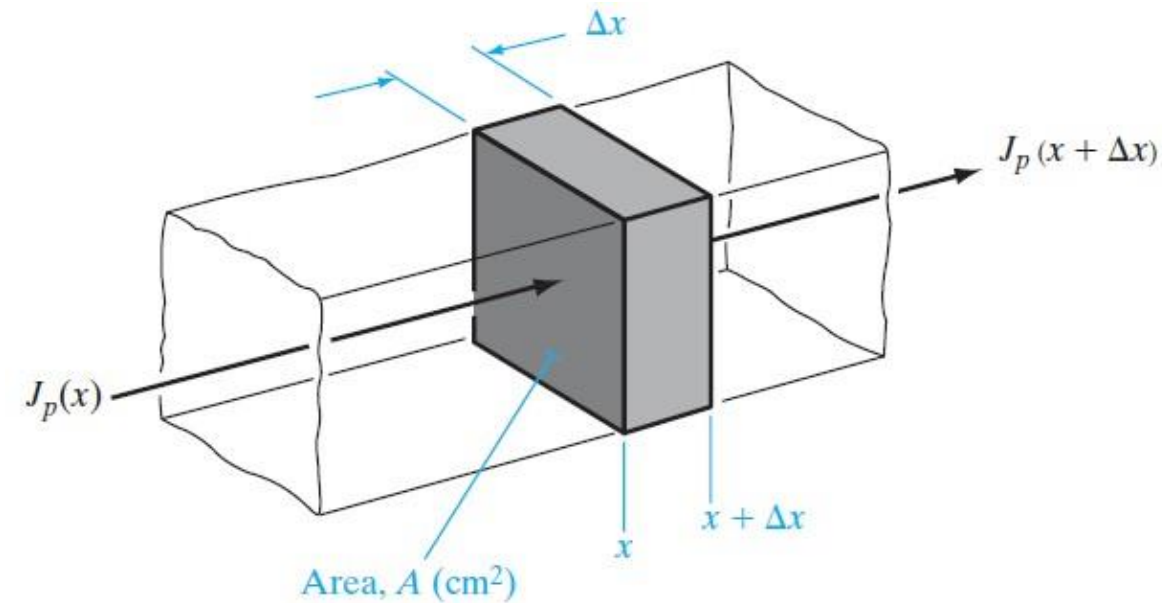


Figure 4.15 | Energy-band diagram showing the redistribution of electrons when donors are added.

$$n_0 = \frac{(N_d - N_a)}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$$

Continuity equation



The time dependent carrier concentrations at different points is given by the carrier continuity equation,

- Consider a differential length (x) of a semiconductor sample with area A in the yz -plane.
- The hole current density leaving the volume, $J_p(x + \Delta x)$, can be larger or smaller than the current density entering, $J_p(x)$, depending on the generation and recombination of carriers taking place within the volume.
- The net increase in hole concentration per unit time, $\partial p / \partial t$, is the difference between the hole flux per unit volume entering and leaving, minus the recombination rate.
- We can convert hole current density to hole particle flux density by dividing J_p by q .
- The current densities are already expressed per unit area; thus dividing $J_p(x)/q$ by Δx gives the number of carriers per unit volume entering $\Delta x A$ per unit time, and $(1/q)J_p(x + \Delta x)/\Delta x$ is the number leaving per unit volume and time:

$$\left. \frac{\partial p}{\partial t} \right|_{x \rightarrow x + \Delta x} = \frac{1}{q} \frac{J_p(x) - J_p(x + \Delta x)}{\Delta x} - \frac{\delta p}{\tau_p} \quad (4-30)$$

Rate of hole buildup = $\frac{\text{increase of hole concentration in } \delta x A \text{ per unit time}}{\text{recombination rate}}$

As Δx approaches zero, we can write the current change in derivative form:

$$\frac{\partial p(x, t)}{\partial t} = \frac{\partial \delta p}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p} \quad (4-31a)$$

The expression (4-31a) is called the *continuity equation* for holes. For electrons we can write

$$\frac{\partial \delta n}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_n} \quad (4-31b)$$

since the electronic charge is negative.

When the current is carried strictly by diffusion (negligible drift), we can replace the currents in Eqs. (4–31) by the expressions for diffusion current; for example, for electron diffusion we have

$$J_n(\text{diff.}) = qD_n \frac{\partial \delta n}{\partial x} \quad (4-32)$$

Substituting this into Eq. (4–31b) we obtain the *diffusion equation* for electrons,

$$\frac{\partial \delta n}{\partial t} = D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau_n} \quad (4-33a)$$

and similarly for holes,

$$\frac{\partial \delta p}{\partial t} = D_p \frac{\partial^2 \delta p}{\partial x^2} - \frac{\delta p}{\tau_p} \quad (4-33b)$$

In many problems a steady state distribution of excess carriers is maintained, such that the time derivatives in Eqs. (4–33) are zero. In the steady state case the diffusion equations become

$$\frac{d^2 \delta n}{dx^2} = \frac{\delta n}{D_n \tau_n} \equiv \frac{\delta n}{L_n^2} \quad (4-34a)$$

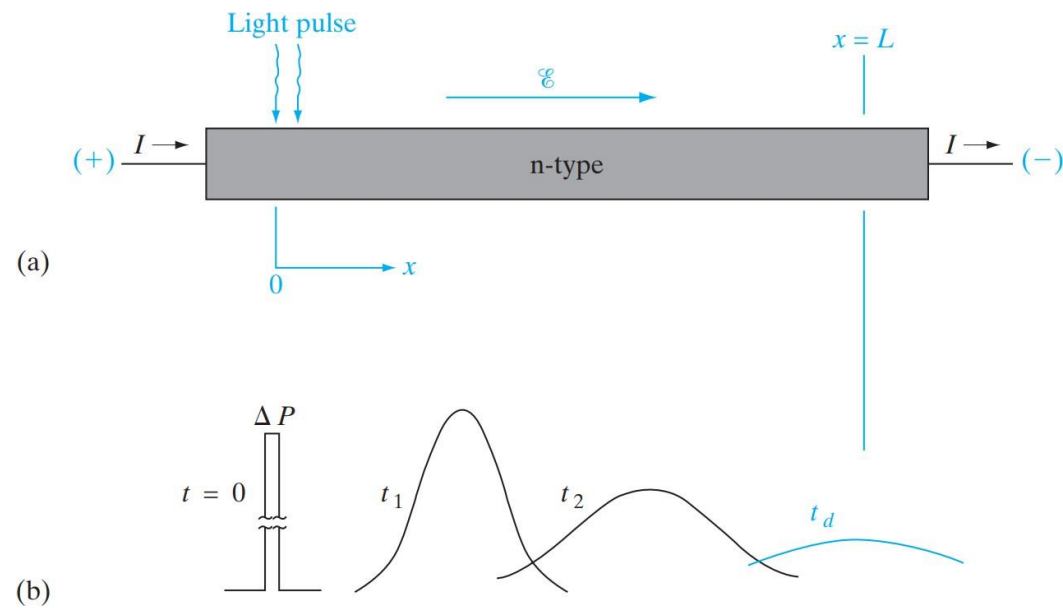
$$\frac{d^2 \delta p}{dx^2} = \frac{\delta p}{D_p \tau_p} \equiv \frac{\delta p}{L_p^2} \quad (4-34b)$$

(steady state)

where $L_n \equiv \sqrt{D_n \tau_n}$ is called the electron *diffusion length* and L_p is the diffusion length for holes. We no longer need partial derivatives, since the time variation is zero for steady state.

Haynes Shockley experiment

- Haynes-Shockley experiment is used to measure the **minority carrier mobility**.
- A pulse of holes is created in an n-type bar (for example) that contains an electric field as the pulse drifts in the field and spreads out by diffusion, the excess hole concentration is monitored at some point down the bar;
 - the time required for the holes to drift a given distance in the field gives a measure of the **mobility**;
 - the spreading of the pulse during a given time is used to calculate the **diffusion coefficient**.
 - In contrast with the Hall effect which can be used with **resistivity** to obtain the **majority carrier mobility**, the Haynes-Shockley experiment is used to measure the minority carrier mobility.



- A pulse of excess carriers is created by a light flash at some point $x = 0$ in an n-type semiconductor ($n_0 \gg p_0$).
- We assume that the excess carriers have a negligible effect on the electron concentration but change the hole concentration significantly.
- The excess holes drift in the direction of the electric field and eventually reach the point $x = L$, where they are monitored.
- By measuring the drift time t_d , we can calculate the drift velocity v_d and, therefore, the hole mobility:

$$v_d = \frac{L}{t_d}$$

$$\mu_p = \frac{v_d}{\mathcal{E}}$$

For the case of negligible recombination (τ_p long compared with the times involved in the diffusion), we can write the diffusion equation as

The function which satisfies this equation is called a *gaussian distribution*,

$$\delta p(x, t) = \left[\frac{\Delta P}{2\sqrt{\pi D_p t}} \right] e^{-x^2/4D_p t} \quad (4-44)$$

$$D_p = \frac{(\Delta x)^2}{16t_d}$$

$$\Delta x = \Delta t v_d = \Delta t \frac{L}{t_d}$$

The pulse width Δt is related to Δx by the drift velocity

Problems

To calculate the diffusion current density given a density gradient.

Assume that, in an n-type gallium arsenide semiconductor at $T = 300$ K, the electron concentration varies linearly from 1×10^{18} to $7 \times 10^{17} \text{ cm}^{-3}$ over a distance of 0.10 cm . Calculate the diffusion current density if the electron diffusion coefficient is $D_n = 225 \text{ cm}^2/\text{s}$.

■ Solution

The diffusion current density is given by

$$\begin{aligned} J_{n,dif} &= eD_n \frac{dn}{dx} \approx eD_n \frac{\Delta n}{\Delta x} \\ &= (1.6 \times 10^{-19})(225) \left(\frac{1 \times 10^{18} - 7 \times 10^{17}}{0.10} \right) = 108 \text{ A/cm}^2 \end{aligned}$$

■ Comment

A significant diffusion current density can be generated in a semiconductor material with only a modest density gradient.

An Si sample is doped with 10^{17} As atom/cm³. The intrinsic concentration for Si at 300 K is $n_i = 1.5 \times 10^{10}$ cm⁻³. Find the equilibrium hole concentration p_0 at 300 K. How is E_F related to E_i ?

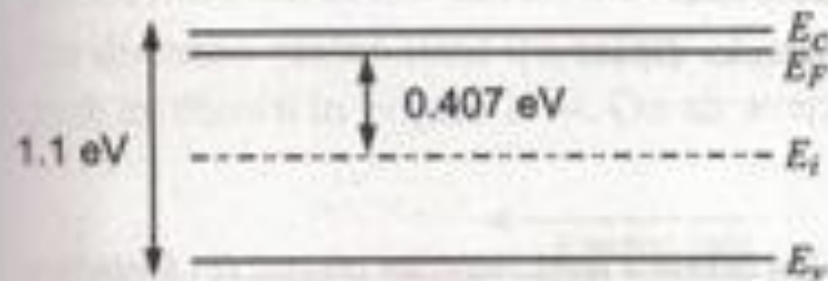
SOLUTION: Here the doped carrier N_d is $\gg n_i$, so we can approximate $n_0 = N_d$ and

$$p_0 = \frac{n_i^2}{n_0} = \frac{2.25 \times 10^{20}}{10^{17}} = 2.25 \times 10^3 \text{ cm}^{-3}$$

From equation (1.88), we have

$$E_F - E_i = kT \ln \frac{n_0}{n_i} = 0.0259 \ln \frac{10^{17}}{1.5 \times 10^{10}} = 0.407 \text{ eV}$$

The resulting band structure is shown in the figure given below



An n-type Ge sample is used in the Haynes–Shockley experiment shown in Fig. 4–20. The length of the sample is 1 cm, and the probes (1) and (2) are separated by 0.95 cm. The battery voltage E_0 is 2 V. A pulse arrives at point (2) 0.25 ms after injection at (1); the width of the pulse Δt is 117 μs . Calculate the hole mobility and diffusion coefficient, and check the results against the Einstein relation.

$$\mu_p = \frac{v_d}{\mathcal{E}} = \frac{0.95 / (0.25 \times 10^{-3})}{2/1} = 1900 \text{ cm}^2/(\text{V}\cdot\text{s})$$

$$\begin{aligned} D_p &= \frac{(\Delta x)^2}{16t_d} = \frac{(\Delta t L)^2}{16t_d^3} \\ &= \frac{(117 \times 0.95)^2 \times 10^{-12}}{16(0.25)^3 \times 10^{-9}} = 49.4 \text{ cm}^2\text{s} \end{aligned}$$

$$\frac{D_p}{\mu_p} = \frac{49.4}{1900} = 0.026 = \frac{kT}{q}$$

