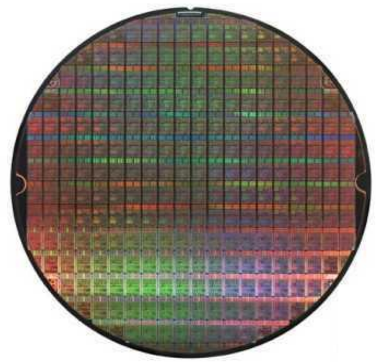


Module – II.2

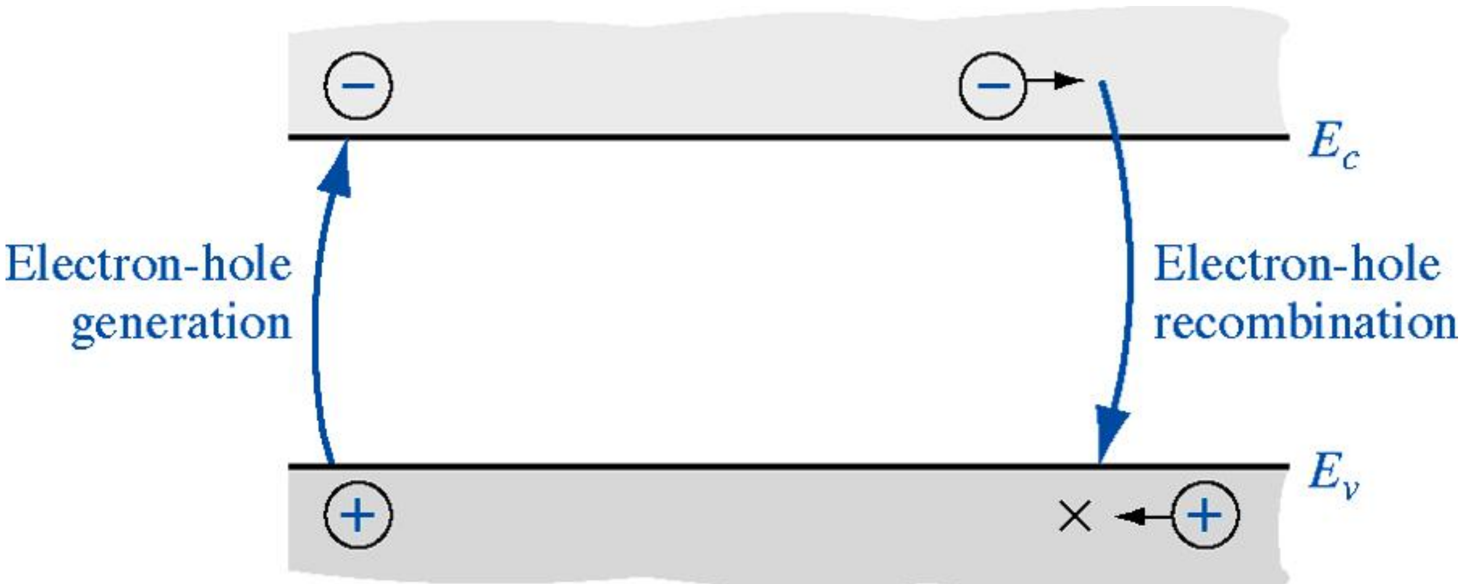
Non-equilibrium Excess Carrier

- **Excess carrier generation and recombination**
- **Continuity equation and time-dependent diffusion equation**

Nonequilibrium Excess Carriers - in Semiconductors

- When a voltage is applied or a current exists in a semiconductor device, the semiconductor is operating under nonequilibrium conditions.
- Excess electrons in the conduction band and excess holes in the valence band may exist in addition to the thermal-equilibrium concentrations if an external excitation is applied to the semiconductor.
- They do not move independently of each other but diffuse, drift, and recombine with the same effective diffusion coefficient, drift mobility, and lifetime; called **ambipolar transport** .

- **Generation** is the process where electrons and holes are created, in **recombination** ,electrons and holes are annihilated.
- An external excitation, can generate electrons and holes, creating a nonequilibrium condition.


Electron-hole
generation
Electron-hole
recombination
E_c
E_v

Carrier Generation

Carriers can be generated through three processes.

1. Thermal generation

(at high temp.)

2. Photon irradiation

Photon energy hν≥ Eg

3. Impact ionisation

(Already created carrier create new carriers

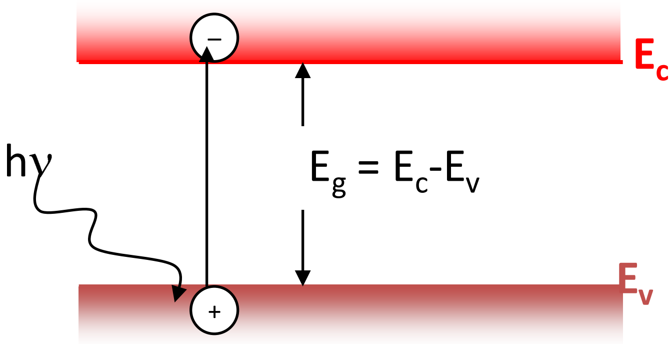


Photo-excitation:

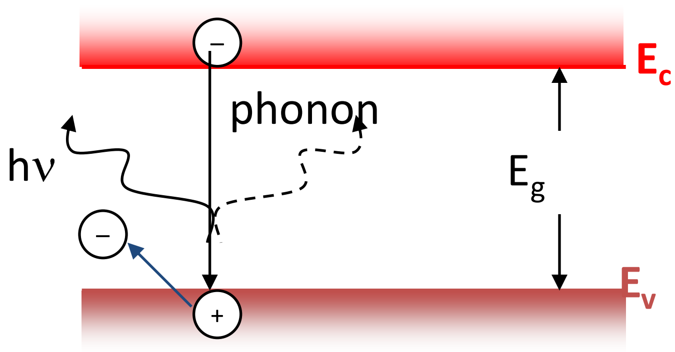
A photon of energy hν can excite an electron from valence band to conduction band if $h\nu > E_g$.

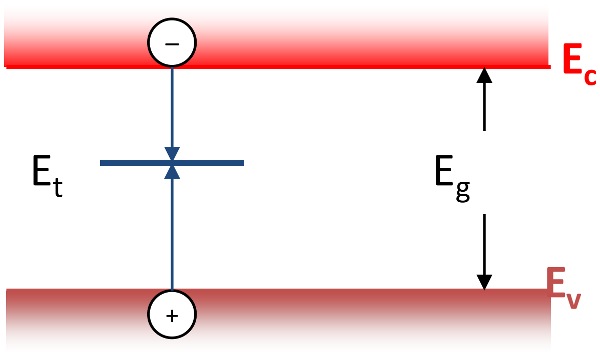
G_{n0} = rate of thermal generation of electrons

G_{p0} = rate of thermal generation of holes

Carrier Recombination

Carrier present in excess of thermal equilibrium will recombine.





Band-to-band Recombination

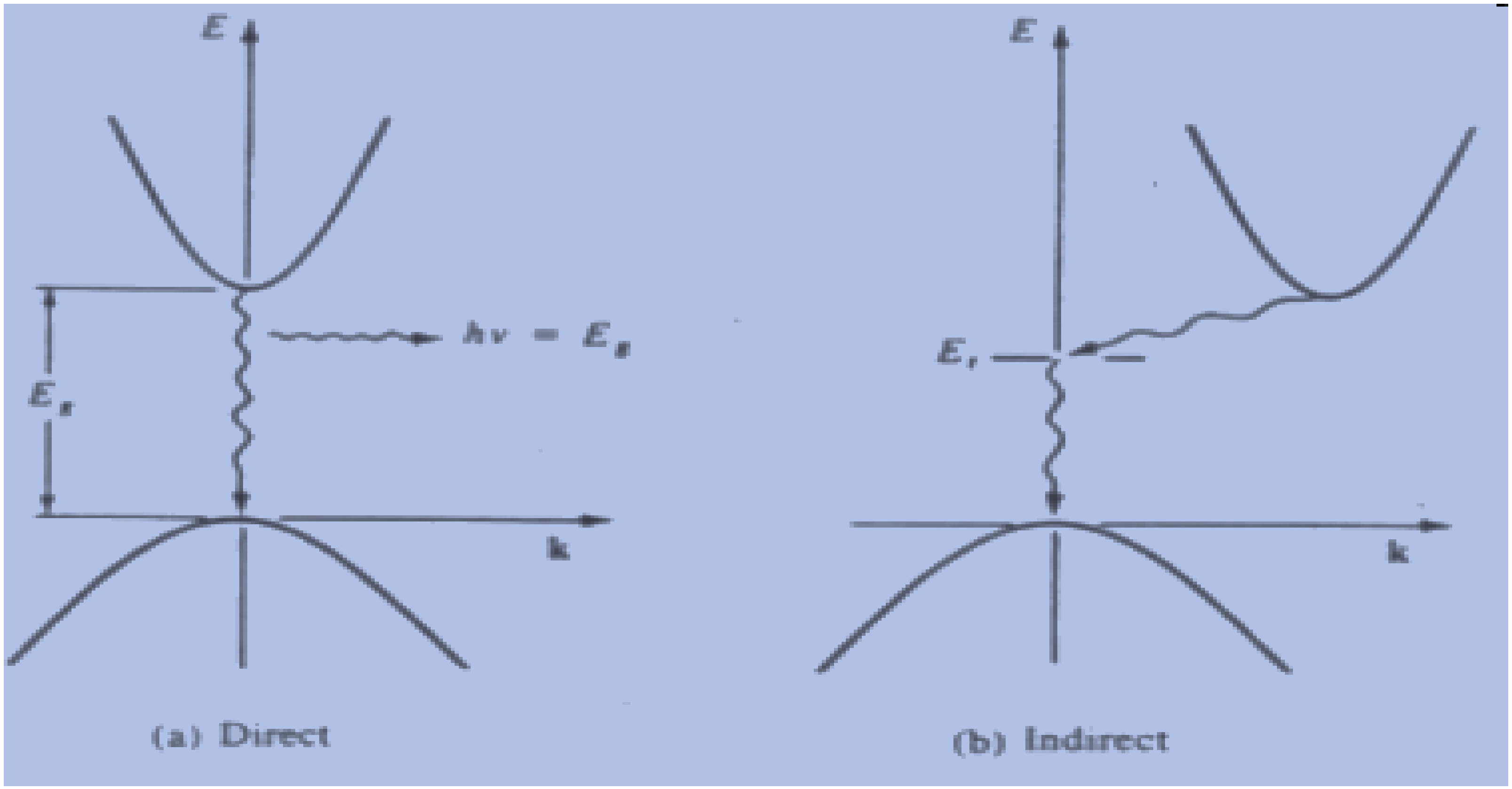
- Radiative recombination – photon or phonon
  $e^- + h^+ \Rightarrow h\nu$ (photon)
- Auger recombination – Photon can knock out an electron

Mid Band Recombination

- A mid-band trap state at E_t present
- e^- and h^+ recombine through the trap centre

R_{n0} = rate of recombination of electrons
R_{p0} = rate of recombination of holes

DIRECT & INDIRECT BAND SEMICONDUCTORS



Direct band gap
Ex: GaAs

Indirect bandgap: ΔK is large but for a direct bandgap: ΔK=0 and *light* in direct bandgap materials (GaAs, GaN, etc) but *heat* in indirect bandgap materials (Si, Ge)

Indirect band gap
Ex: Si,Ge

Semiconductor in Equilibrium

- In thermal equilibrium, electron & hole concentrations are independent of time.

- Electrons are continuously excited thermally from the valence band into the conduction band randomly.

- At the same time, electrons moving randomly in the crystal may combine with a holes which annihilates both the electron and hole.

- **Since the net carrier concentrations are independent of time in thermal equilibrium, the rate at which electrons and holes are generated and the rate at which they recombine must be equal**

Since thermal generation leads to creation of an electron-hole pair,

$$G_{n0} = G_{p0}$$

Since recombination is in pairs of electrons and holes,

$$R_{n0} = R_{p0}$$

Under thermal equilibrium, $G_{n0} = G_{p0} = R_{n0} = R_{p0}$

Excess carriers in a semiconductor (nonequilibrium):-

Due to external excitation an electron is created in the conduction band, and a hole in the valence band (electron-hole pair is generated)

The additional electrons and holes created are called ***excess electrons and excess holes.***

So $n > n_0$ & $p > p_0$

For the direct band-to-band generation, the excess electrons and holes are also created in pairs, so if

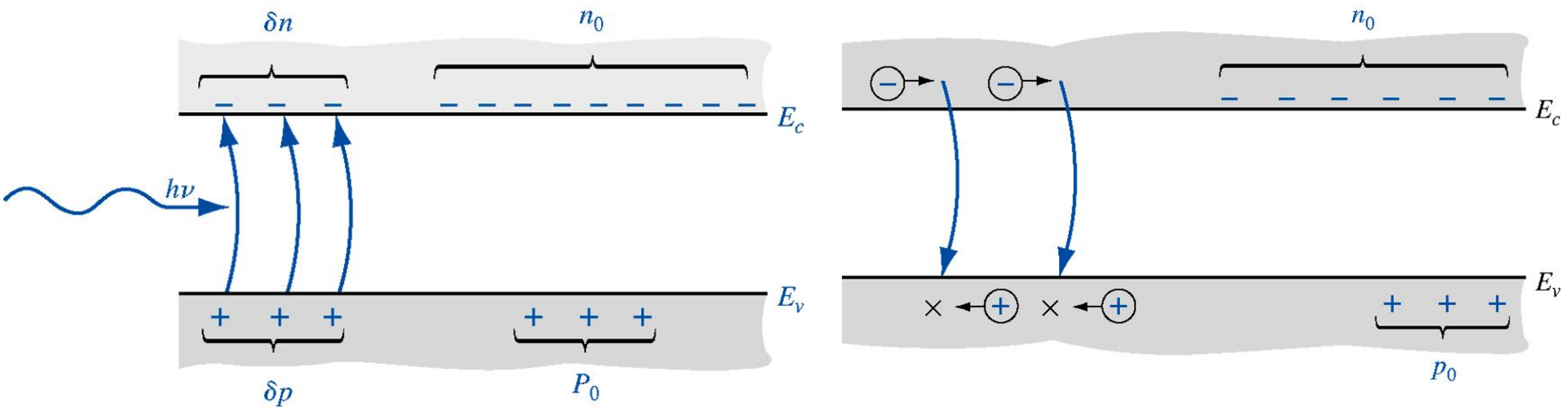
g'_n be the generation rate of excess electrons and g'_p be that of excess holes

$$g'_n = g'_p$$

➢ When excess electrons (**δn**) and holes (**δp**) are created, the concentration of electrons in the conduction band and of holes in the valence band increase above their thermal equilibrium value

$$n = n_0 + \delta n$$

$$p = p_0 + \delta p$$



In a nonequilibrium condition, $np \neq n_0 p_0 = n_i^2$.

If recombination rate for excess electrons is denoted by R_n', and for excess holes by R_p'

As the excess electrons and holes recombine in pairs, so the recombination rates must be equal

$$R_n' = R_p'$$

The rate at which electrons **recombine** is proportional to the electron concentration and hole concentration.

$$\frac{dn(t)}{dt} = \alpha_r \left[n_i^2 - n(t)p(t) \right]$$

$$n(t) = n_0 + \delta n(t)$$

$$p(t) = p_0 + \delta p(t)$$

As excess electrons and holes are created and recombine in pairs,

$$\delta n(t) = \delta p(t)$$

As n_0 and p_0, being independent of time

$$\frac{d(\delta n(t))}{dt} = \alpha_r\left[n_i^2 - (n_0 + \delta n(t))(p_0 + \delta p(t))\right]$$
$$= -\alpha_r \delta n(t)[(n_0 + p_0) + \delta n(t)]$$

- **Low-level injection :-** excess carrier concentration is much less than the thermal equilibrium majority carrier concentration.

- **High-level injection;-** excess carrier concentration is comparable to or greater than the thermal equilibrium majority carrier concentrations.

In a p-type semiconductor, $p_0 \gg n_0$.

For low-level injection, **$\delta n(t) << p_0$**

$$So, \quad \frac{d(\delta n(t))}{dt} = -\alpha_r p_0 \delta n(t)$$

solution to the equation is an exponential decay from the initial excess concentration,

$$\delta n(t) = \delta n(0) e^{-\alpha_r p_0 t} = \delta n(0) e^{-t/\tau_{n0}}$$

Where excess minority carrier lifetime is given as,

$$\tau_{n0} = (\alpha_r p_0)^{-1}$$

The recombination rate of excess minority carrier electrons

$$R_n' = \frac{-d(\delta n(t))}{dt} = +\alpha_r p_0 \delta n(t) = \frac{\delta n(t)}{\tau_{n0}}$$

For the direct band-to-band recombination, the excess majority carrier holes recombine at the same rate, so that for the P-type material

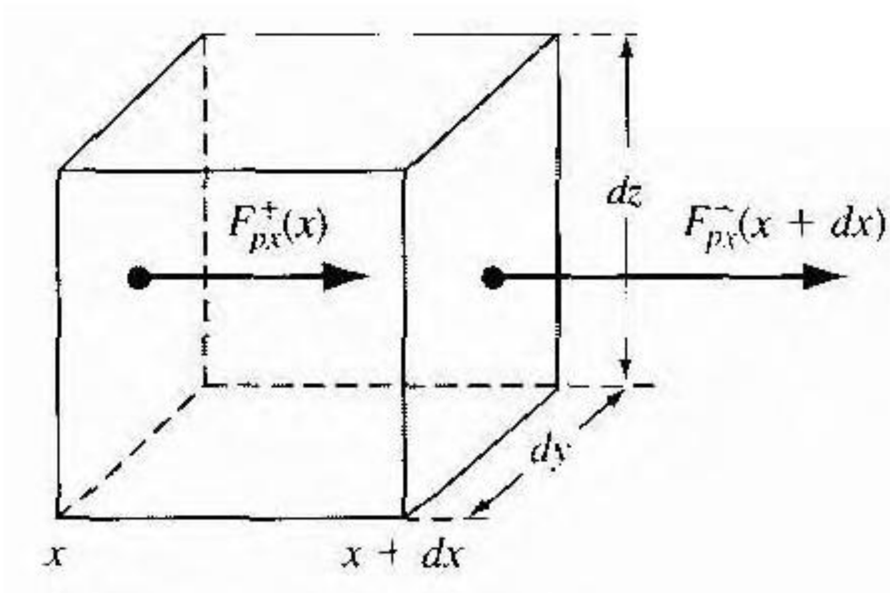
$$R_n' = R_p' = \frac{\delta n(t)}{\tau_{n0}}$$

Similarly for N-type material,

$$R_n' = R_p' = \frac{\delta p(t)}{\tau_{p0}}$$

Generation and recombination rates are functions of the space coordinates and time.

Continuity Equations



In the small differential volume,
Considering the hole particle flux
In between x and x+dx

$$F_{px}^{+}(x+dx) = F_{px}^{+}(x) + \frac{\partial F_{px}^{+}}{\partial x} \cdot dx$$

Due to the hole flow along X-direction, the increase in the number of holes per unit time within the differential volume element dx dy dz is

$$\frac{\partial p}{\partial t} dx\, dy\, dz = [F_{px}^{+}(x) - F_{px}^{+}(x + dx)]\, dy\, dz = -\frac{\partial F_{px}^{+}}{\partial x} dx\, dy\, dz$$

As the generation rate and recombination rate of holes will also affect the hole concentration in the differential volume, the net increase in the number of holes per unit time in the differential volume element is given by

$$\frac{\partial p}{\partial t} dx\, dy\, dz = -\frac{\partial F_{p}^{+}}{\partial x} dx\, dy\, dz + g_p\, dx\, dy\, dz - \frac{p}{\tau_{pt}} dx\, dy\, dz$$

Where, τ_{pt} includes the thermal equilibrium carrier lifetime and the excess carrier lifetime

$$\frac{\partial p}{\partial t} = -\frac{\partial F_p^+}{\partial x} + g_p - \frac{p}{\tau_{pt}}$$

$$\frac{\partial n}{\partial t} = -\frac{\partial F_n^-}{\partial x} + g_n - \frac{n}{\tau_{nt}}$$

One dimensional Continuity equations for electrons and holes

Time-Dependent Diffusion Equations:

The hole and electron currents are given as

$$J_p = e\mu_p p\mathrm{E} - eD_p\frac{\partial p}{\partial x}$$

$$J_n = e\mu_n n\mathrm{E} + eD_n\frac{\partial n}{\partial x}$$

So, hole and electron particle flux are:

$$\frac{J_p}{(+e)} = F_p^+ = \mu_p p\mathrm{E} - D_p\frac{\partial p}{\partial x}$$

$$\frac{J_n}{(-e)} = F_n^- = -\mu_n n\mathrm{E} - D_n\frac{\partial n}{\partial x}$$

$$\frac{\partial}{\partial x} F_p^+ = \mu_p \frac{\partial}{\partial x}(pE) - D_p \frac{\partial^2 p}{\partial x^2}$$

$$\& \frac{\partial}{\partial x} F_n^- = -\mu_n \frac{\partial}{\partial x}(nE) - D_n \frac{\partial^2 n}{\partial x^2}$$

Substituting in the continuity equations

$$\frac{\partial p}{\partial t} = -\mu_p \frac{\partial(p\mathrm{E})}{\partial x} + D_p \frac{\partial^2 p}{\partial x^2} + g_p - \frac{p}{\tau_{pt}}$$

$$\frac{\partial n}{\partial t} = +\mu_n \frac{\partial(n\mathrm{E})}{\partial x} + D_n \frac{\partial^2 n}{\partial x^2} + g_n - \frac{n}{\tau_{nt}}$$

$$\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \mu_p \left(\mathrm{E} \frac{\partial p}{\partial x} + p \frac{\partial \mathrm{E}}{\partial x} \right) + g_p - \frac{P}{\tau_{pt}}$$

similarly,

$$\frac{\partial n}{\partial t} = D_n \frac{\partial^2 n}{\partial x^2} + \mu_n \left(\mathrm{E} \frac{\partial n}{\partial x} + n \frac{\partial \mathrm{E}}{\partial x} \right) + g_n - \frac{n}{\tau_{nt}}$$

As

$$n = n_0 + \delta n$$

$$p = p_0 + \delta p$$

and n_0 and p_0 are independent of space and time the above equations can be written for the excess carrier conc. w.r.t. space and time as follows:

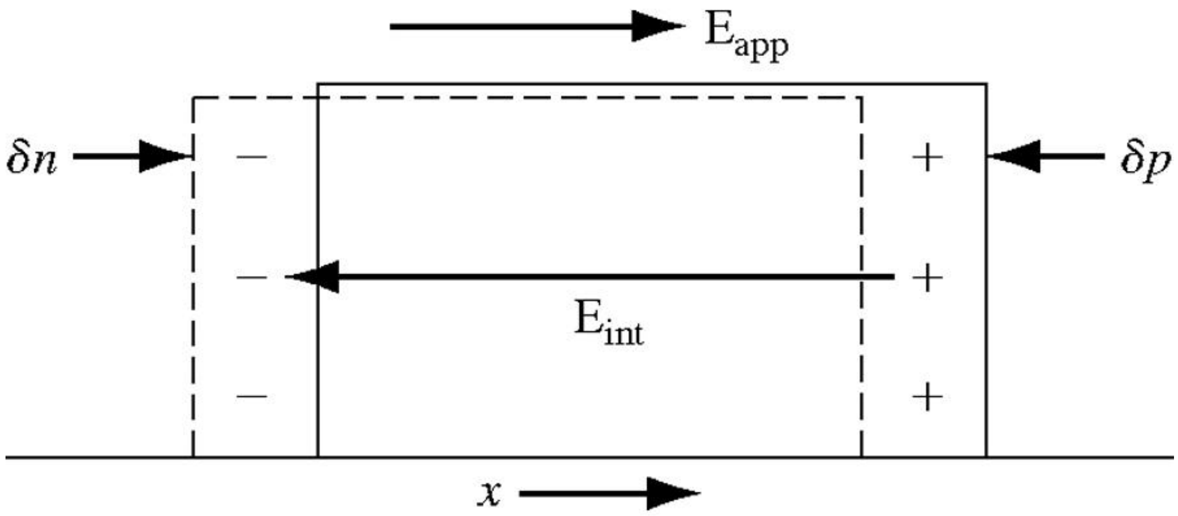
$$D_p \frac{\partial^2 (\delta p)}{\partial x^2} - \mu_p \left(\mathrm{E} \frac{\partial (\delta p)}{\partial x} + p \frac{\partial \mathrm{E}}{\partial x} \right) + g_p - \frac{p}{\tau_{pt}} = \frac{-\partial (\delta p)}{\partial t}$$

$$D_n \frac{\partial^2 (\delta n)}{\partial x^2} + \mu_n \left(\mathrm{E} \frac{\partial (\delta n)}{\partial x} + n \frac{\partial \mathrm{E}}{\partial x} \right) + g_n - \frac{n}{\tau_{nt}} = \frac{\partial (\delta n)}{\partial t}$$

Ambipolar transport

The excess electrons and holes do not move independently of each other, but they diffuse and drift with the same effective diffusion coefficient and with the same effective mobility under the application of external electric field. The transport of excess carriers and their space and time dependence is called **ambipolar transport.**

AMBIPOLAR TRANSPORT



- Excess holes and electrons created will tend to drift in opposite directions.

- Separation of charges will induce an internal electric field.

- This internal electric field will create a force attracting the electrons and holes back toward each other and will hold them together.

- 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 transport**.

$E_{int} << E_{appl}$

As $g_n = g_p = g$

$$R_n = \frac{n}{\tau_{nt}} = R_p = \frac{p}{\tau_{pt}} \equiv R$$

Then using the charge neutrality condition $\delta n = \delta p$, we can write

$$D_p \frac{\partial^2(\delta n)}{\partial x^2} - \mu_p \left(\mathrm{E} \frac{\partial(\delta n)}{\partial x} + p \frac{\partial \mathrm{E}}{\partial x} \right) + g - R = \frac{\partial(\delta n)}{\partial t}$$

And

$$D_n \frac{\partial^2(\delta n)}{\partial x^2} + \mu_n \left(\mathrm{E} \frac{\partial(\delta n)}{\partial x} + n \frac{\partial \mathrm{E}}{\partial x} \right) + g - R = \frac{\partial(\delta n)}{\partial t}$$

Multiplying (1) by μ_n n and (2) by μ_p n and then adding the two

$$(\mu_n n D_p + \mu_p p D_n)\frac{\partial^2(\delta n)}{\partial x^2} + (\mu_n \mu_p)(p - n)\mathrm{E}\frac{\partial(\delta n)}{\partial x}$$

$$+ (\mu_n n + \mu_p p)(g - R) = (\mu_n n + \mu_p p)\frac{\partial(\delta n)}{\partial t}$$

Dividing the equation by **μ_nn+ μ_pn**

$$D'\frac{\partial^2(\delta n)}{\partial x^2} + \mu'\mathrm{E}\frac{\partial(\delta n)}{\partial x} + g - R = \frac{\partial(\delta n)}{\partial t}$$

Is the ambipolar transport equation describes the behavior of the excess electrons and holes in time and space. The parameter D' is called the ambipolar diffusion coefficient and μ' is called ambipolar mobility

Where

$$D' = \frac{\mu_n n D_p + \mu_p p D_n}{\mu_n n + \mu_p p}$$

And

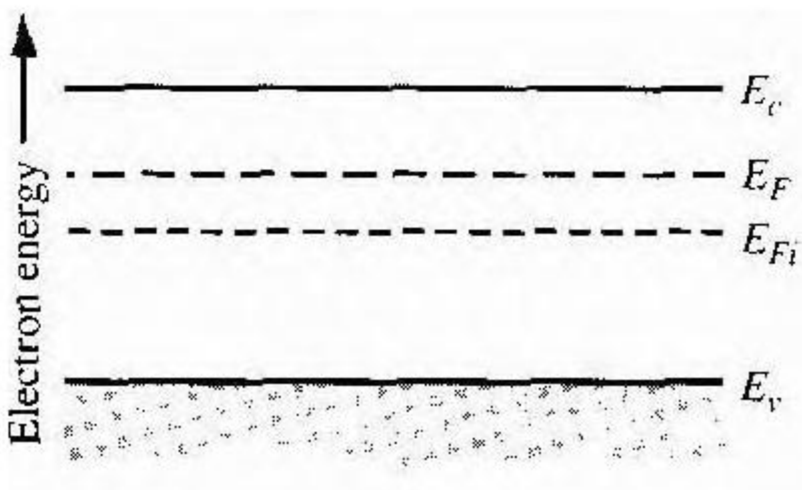
$$\mu' = \frac{\mu_n \mu_p (p - n)}{\mu_n n + \mu_p p}$$

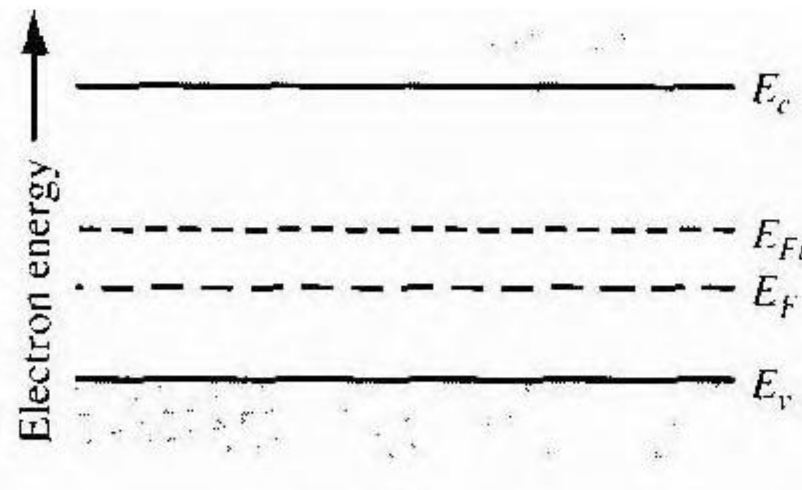
QUASI-FERMI ENERGY LEVELS

$$so,\ n_0 = n_i e^{\frac{(E_F - E_{Fi})}{kT}}$$

$$and\ p_0 = n_i e^{\frac{(E_{Fi} - E_F)}{kT}}$$

For N-type $E_F > E_{Fi}$ and for P-type $E_{Fi} > E_F$





For excess carriers in a semiconductor (Non-equilibrium)

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

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

E_{Fn} and E_{Fp} are the quasi-Fermi energy levels for electrons and holes.

For low-injection condition, the quasi-Fermi level for electrons is not much different from the thermal-equilibrium Fermi level.
The quasi-Fermi energy level for the minority carrier holes is significantly different from the Fermi level