
Chapter

4

CARRIER DYNAMICS IN SEMICONDUCTORS



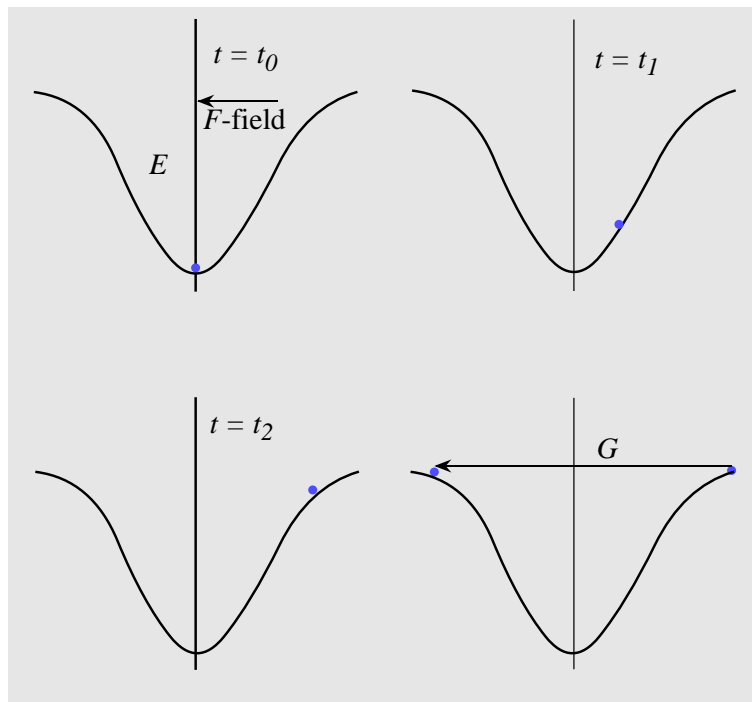
In this chapter we enclose figures that provide an overview of how electrons and holes respond to electric fields, concentration gradients, and optical radiation. We also discuss the nonradiative recombination of electrons and holes, the continuity equation, and diffusion length.

TRANSPORT AND SCATTERING OF CARRIERS

In a perfectly periodic material, electrons suffer no scattering and obey the equation

$$\hbar \frac{dk}{dt} = \text{Force}$$

If an electric field is applied the electrons will oscillate in k -space—from the $k=0$ to zone edge k -value, as shown. Such oscillations are called *Bloch Zener oscillations* and can, in principle, generate terahertz radiation. However, in real semiconductors scattering occurs and destroys the possibility of these oscillations.



The motion of an electron in a band in the absence of any scattering and in the presence of an electric field. The electron oscillates in k -space gaining and losing energy from the field.

SCATTERING OF ELECTRONS (HOLES) AND MOBILITY

As electrons move in semiconductors they scatter from impurities, thermal vibrations of the atoms, and structural defects

After a time τ_{sc} , electrons, on average, lose coherence with their starting momentum. The average drift velocity in an electric field is

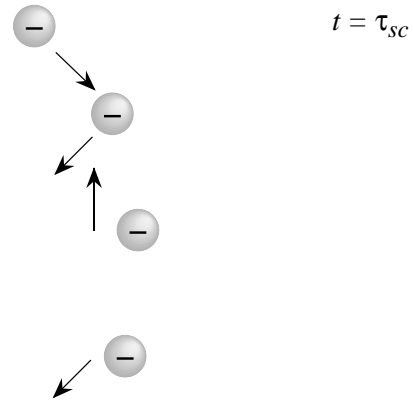
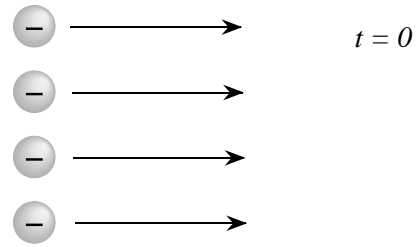
$$v = \frac{eF\tau_{sc}}{m^*}$$

The mobility of the mobile carriers:

$$\mu = \frac{e\tau_{sc}}{m^*}$$

Conductivity

$$\sigma = ne\mu_n + pe\mu_p$$



- Mobility is high if the effective mass is small.
- Loss scattering implies large τ_{sc} and high mobility.

MOBILITIES OF SOME PURE SEMICONDUCTORS

Semiconductor	Mobility at 300 K (cm ² /V • s)	
	Electrons	Holes
C	800	1200
Ge	3900	1900
Si	1500	450
α-SiC	400	50
GaSb	5000	850
GaAs	8500	400
GaP	110	75
InAs	33000	460
InP	4600	150
CdTe	1050	100

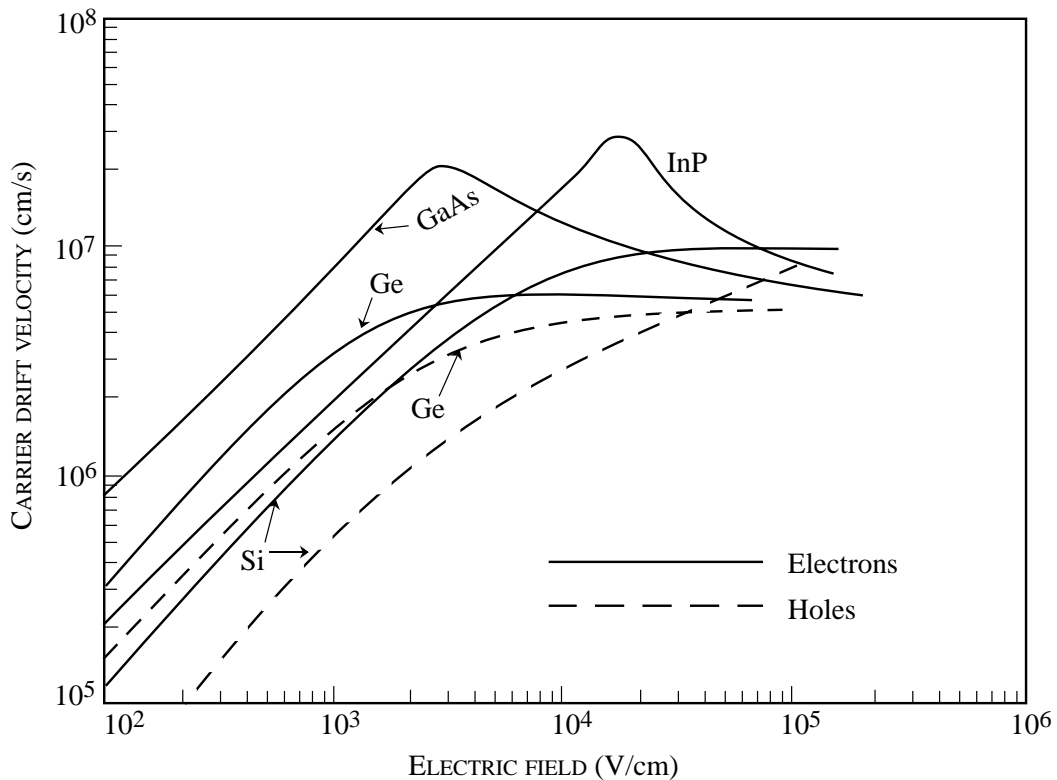
- As semiconductors are doped, electrons (holes) scatter from the dopants and mobility decreases.
- As temperature is lowered the atoms vibrate with smaller amplitude and thus cause less scattering. As a result, mobility increases as temperature is lowered.

HIGH FIELD TRANSPORT

At low electric fields the drift velocity of electrons is proportional to the field

$$v = \mu F$$

At high electric fields the velocity tends to saturate.



At high electric fields, electrons gain energy from the electric field. Their energy is much larger than the zero field energy of $3/2 k_B T$. These “hot” electrons suffer increased scattering and the velocity saturates. The saturation velocity for most semiconductors is $\sim 10^7$ cm/s.

VERY HIGH FIELD TRANSPORT

At very high electric fields electrons gain so much energy that they can excite an electron from the valence band into the conduction band. When this happens we get an extra electron-hole pair. This process is called *impact ionization* or *avalanche breakdown*.

BREAKDOWN ELECTRIC FIELDS IN MATERIALS

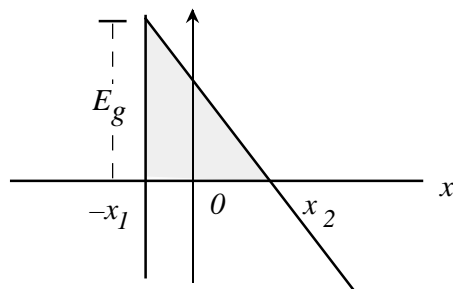
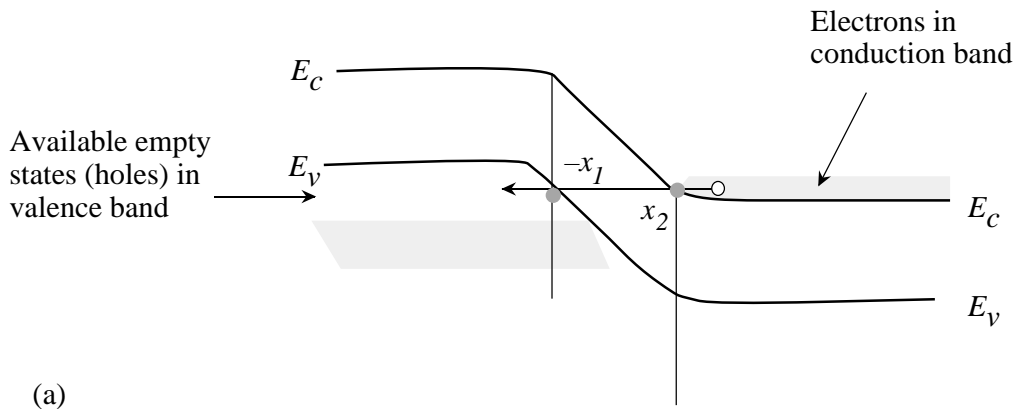
Material	Bandgap (eV)	Breakdown electric field (V/cm)
GaAs	1.43	4×10^5
Ge	0.664	10^5
InP	1.34	
Si	1.1	3×10^5
$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	0.8	2×10^5
C	5.5	10^7
SiC	2.9	$2\text{-}3 \times 10^6$
SiO_2	9	$\sim 10^7$
Si_3N_4	5	$\sim 10^7$

For high power devices avalanche breakdown limits the power output of the device, since beyond a certain bias the current “runs away.” Large bandgap material that can sustain a higher electric field are more suitable for high power devices.

In a class of photodetectors called avalanche photodetectors the avalanche process is used to generate a high number of electrons and holes. This increases the gain of the device, i.e., the number of carriers generated for each photon.

BAND TO BAND TUNNELING AT HIGH ELECTRIC FIELDS

At very high electric fields electrons can tunnel from the valence band to the conduction band (or vice versa). This tunneling causes a large current to flow.



Tunneling probability

$$T = \exp\left(-\frac{4\sqrt{2m^*} E_g^{3/2}}{3e\hbar F}\right)$$

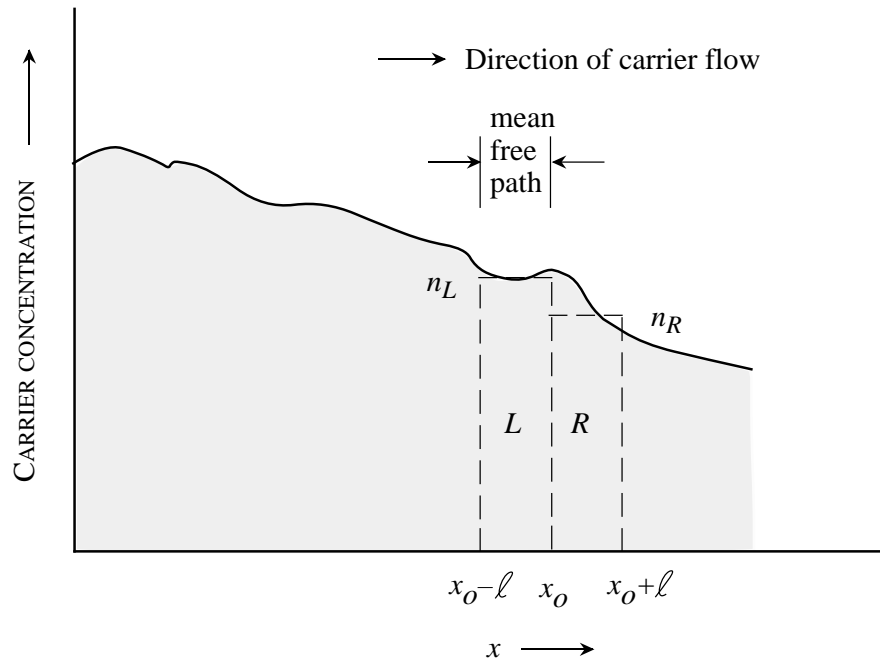
F = electric field across the semiconductor.

Tunneling is high in narrow bandgap materials.

- Band to band tunneling is exploited in Zener diode and Esaki diode.

TRANSPORT BY DIFFUSION

If there is a concentration gradient in the carrier density in a material, carriers will flow from a region of high concentration to a region of low concentration.



$$\begin{aligned}
 J(\text{diffusion}) &= J_n(\text{diff}) + J_p(\text{diff}) \\
 &= eD_n \frac{dn}{dx} - eD_p \frac{dp}{dx}
 \end{aligned}$$

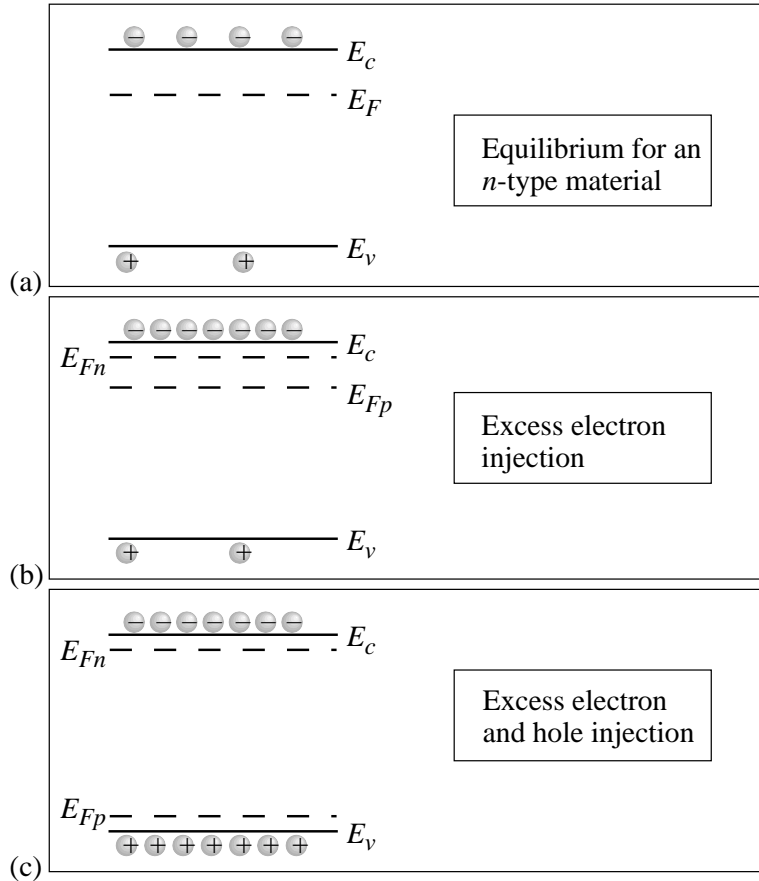
	D_n (cm ² /s)	D_p (cm ² /s)	μ_n (cm ² /V · s)	μ_p (cm ² /V · s)
Ge	100	50	3900	1900
Si	35	12.5	1350	480
GaAs	220	10	8500	400

Einstein relation

$$D = \frac{\mu k_B T}{e}$$

QUASI-FERMI LEVELS

In equilibrium a single energy band—Fermi level—describes the electron and hole densities. In nonequilibrium (i.e., if a field or radiation is present) separate Fermi levels are needed for the conduction band and valence band.



Electron quasi-Fermi level, E_{Fn} gives the electron occupation

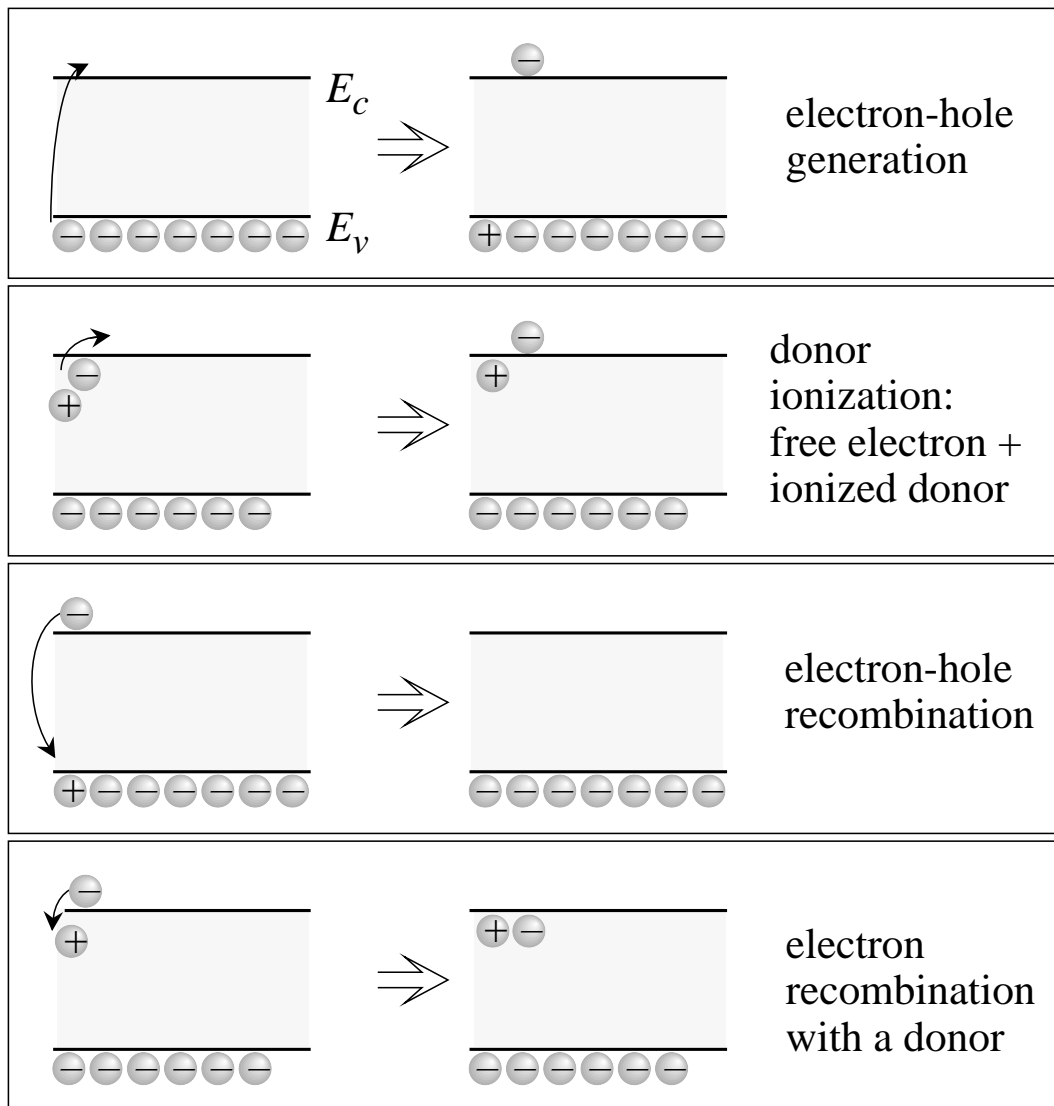
$$f^e(E) = \frac{1}{\exp \frac{E-E_{Fn}}{k_B T} + 1} \quad \text{or} \quad f^e(E) \simeq \exp - \left(\frac{E-E_{Fn}}{k_B T} \right)$$

A separate hole quasi-Fermi level, E_{Fp} describes the hole occupation

$$f^h(E) = \frac{1}{\exp \frac{E-E_{Fp}}{k_B T} + 1} \quad \text{or} \quad f^h(E) \simeq \exp - \left(\frac{E_{Fp}-E}{k_B T} \right)$$

ELECTRON-HOLE GENERATION AND RECOMBINATION

Electrons and holes can be generated in a semiconductor by optical radiation and thermal energy. Electrons and holes can also recombine by emitting light or by emitting heat.

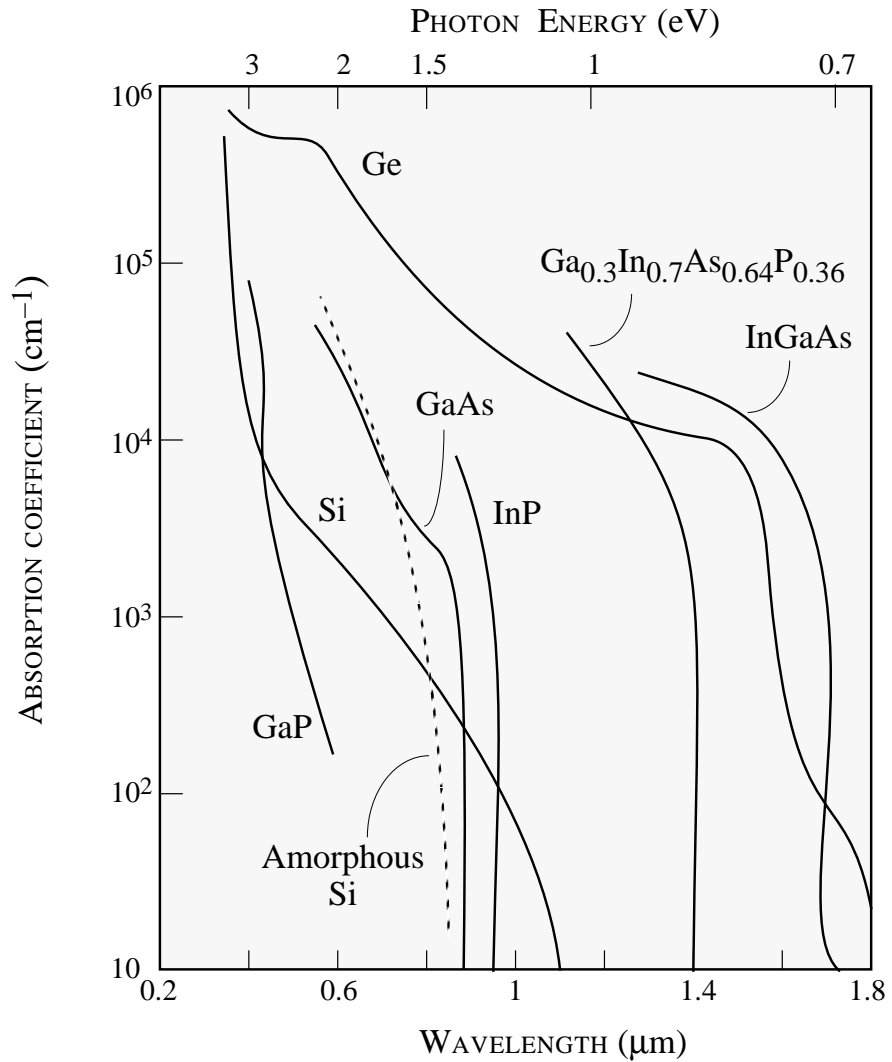


OPTICAL ABSORPTION IN SEMICONDUCTORS

When light shines on a semiconductor it can cause an electron in the valence band to go into the conduction band thus creating an $e-h$ pair.

- Photon energy
 $\hbar\omega > E_g$

- Momentum must be conserved \rightarrow absorption is stronger in direct bandgap materials.



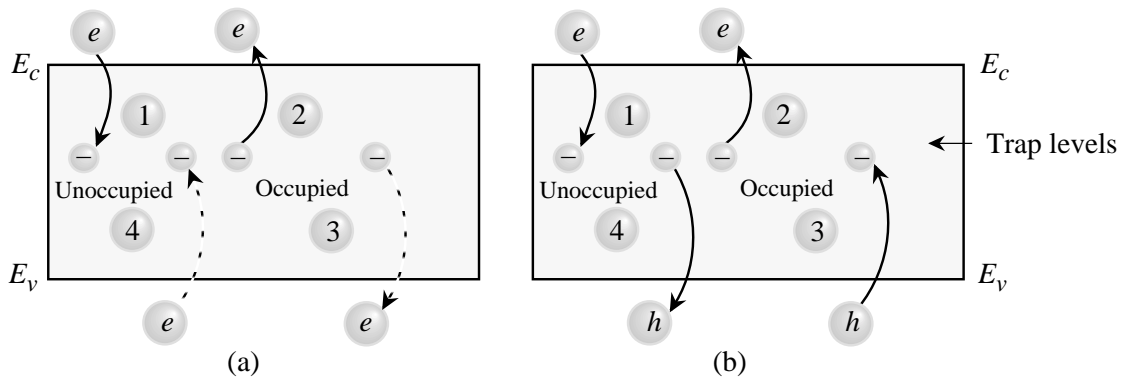
Rate of $e-h$ pair generation (α : absorption coefficient;
 \tilde{p} : optical power density)

$$R_G = \frac{\alpha \tilde{p}}{\hbar\omega}$$

ELECTRON-HOLE RECOMBINATION

Electrons can recombine with holes and generate light \rightarrow this is called *radiative recombination* and is described by a recombination time τ_r .

Electrons can also recombine with holes via impurities as shown and simply emit heat \rightarrow this is *nonradiative recombination* and is described by a time τ_{nr} .



Nonradiative lifetime, τ_{nr} : average time for an electron-hole pair to recombine

$$\frac{1}{\tau_{nr}} = N_t \sigma v_{th}$$

N_t : impurity density

σ : cross-section of the impurity

v_{th} : thermal velocity

Total nonradiative recombination rate

$$R_R \cong \frac{n_p}{\tau_{nr}(n+p)}$$

Schockley-Read-Hall recombination

Total recombination time τ

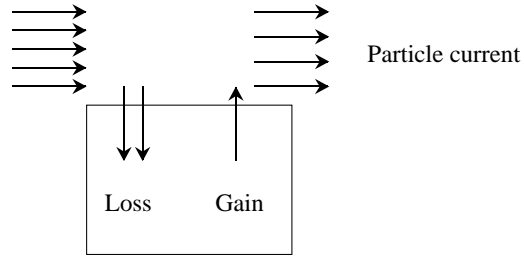
$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

CONTINUITY EQUATION FOR CARRIERS IN SEMICONDUCTORS

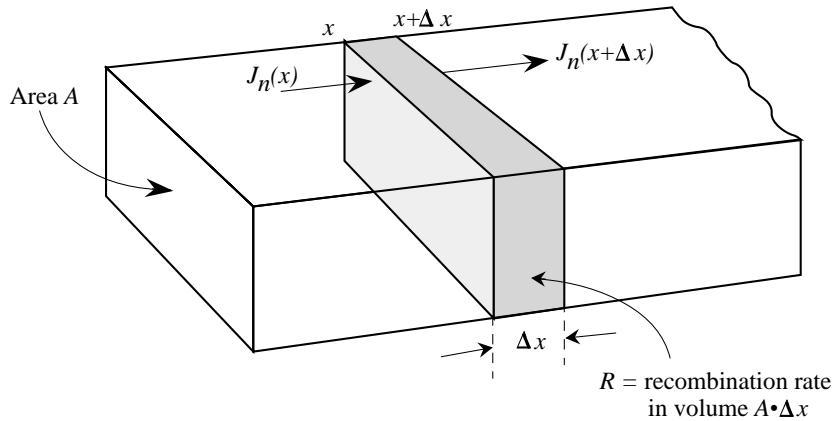
The continuity equation allows us to calculate the carrier distribution in the presence of generation and recombination.

Continuity equation \implies Conservation of electrons and hole densities

Total rate of particle flow = Particle flow due to current – Loss due to recombination rate = Gain due to generation rate



(a)



(b)

G : generation rate

L_n : diffusion length for electrons = $D_n \tau_n$

L_p : diffusion length for holes = $D_p \tau_p$

$$\frac{d^2 \delta_n}{dx^2} = \frac{\delta_n}{L_n^2} - G$$

$$\frac{d^2 \delta_p}{dx^2} = \frac{\delta_p}{L_p^2} - G$$

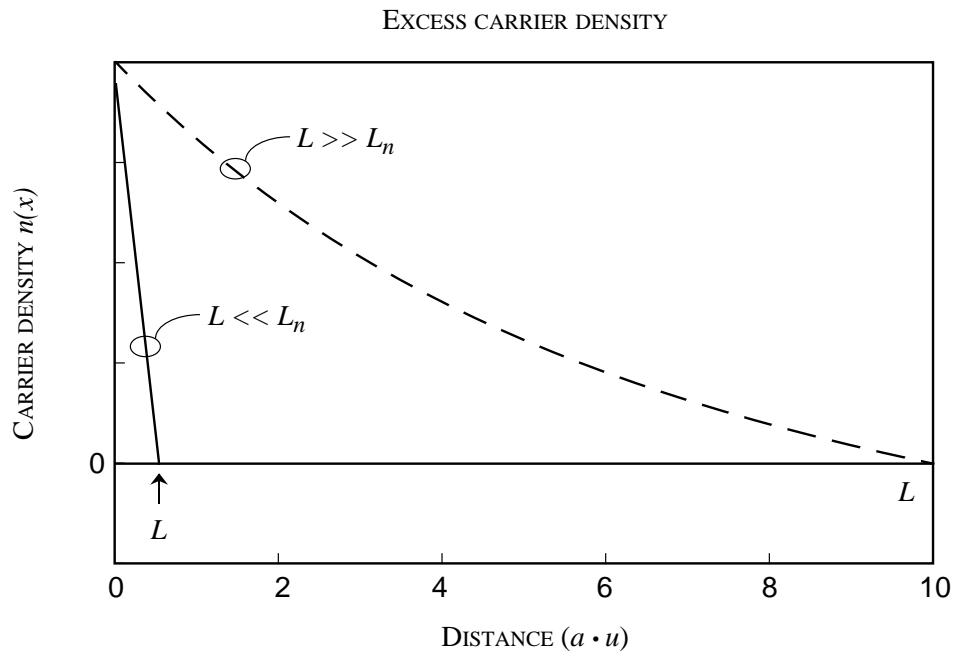
CARRIER INJECTION AND CARRIER DISTRIBUTION

If excess carrier density is injected into a material, the carriers decay by recombination.

If the carrier concentration is fixed at $x = 0$ and $x = L$ we find the following:

If $L \ll L_n$: Carrier distribution is linear

If $L \gg L_n$: Carrier distribution is exponential



If carriers are injected across a region of width W and $W \ll$ diffusion length, the transit time across the region is:

$$t_{tr} = \frac{W^2}{2D}$$