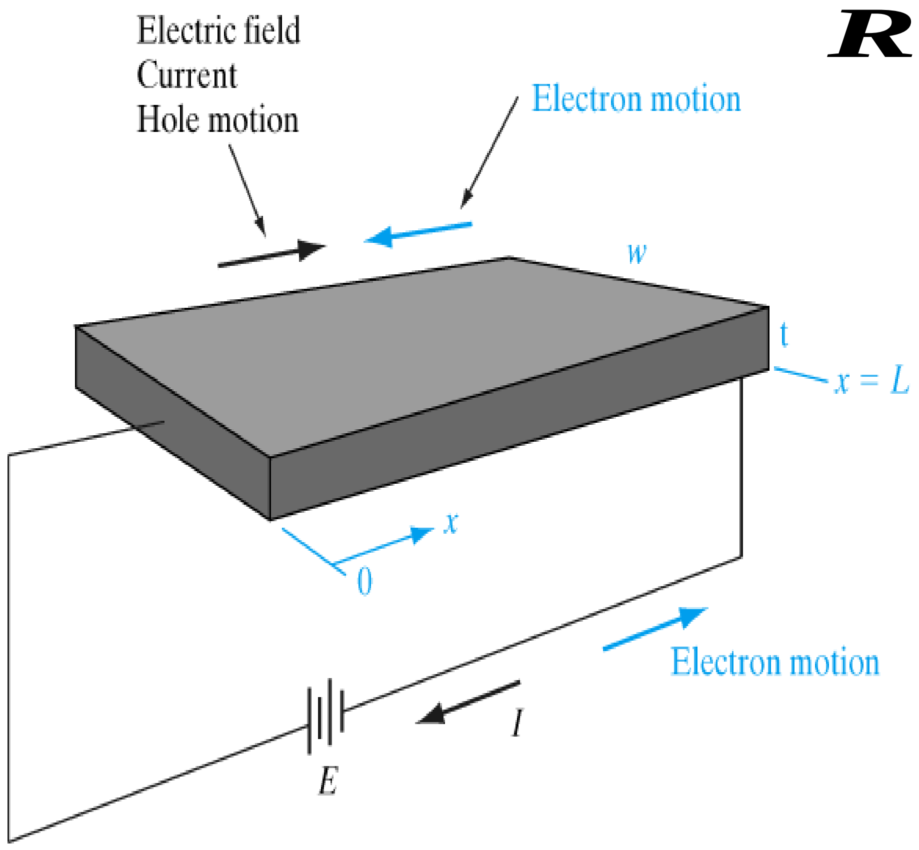
Electronic Devices

Lecture 9

30-08-2018

Drift of electrons and holes in a semiconductor bar

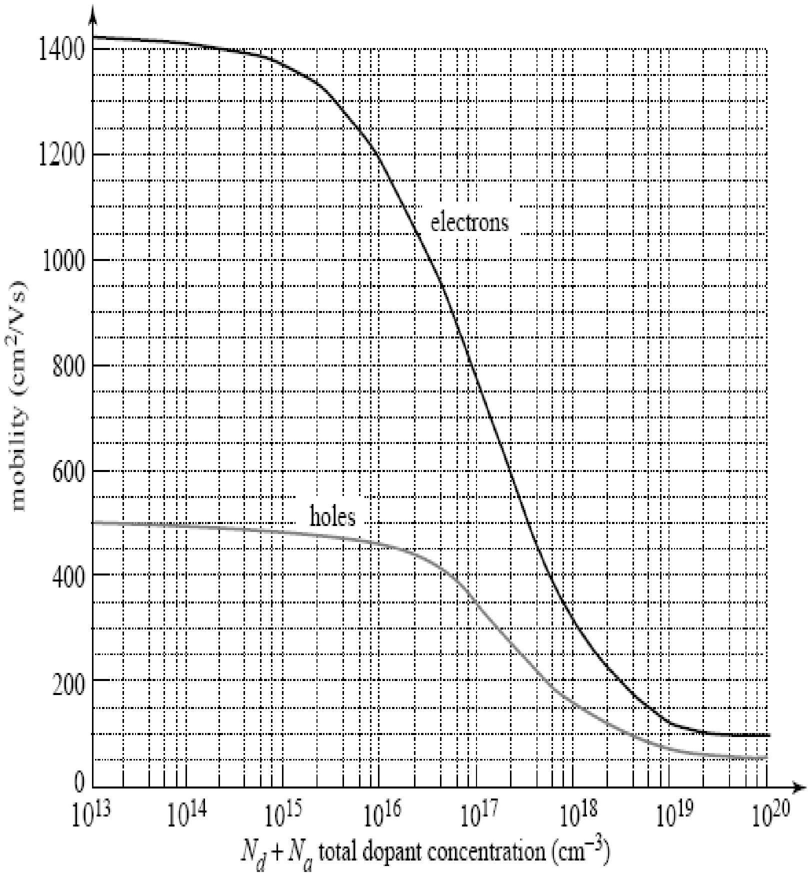
$$R = \frac{\rho L}{wt} = \frac{L}{wt}\frac{1}{\sigma}$$



Effect of temperature and doping on mobility

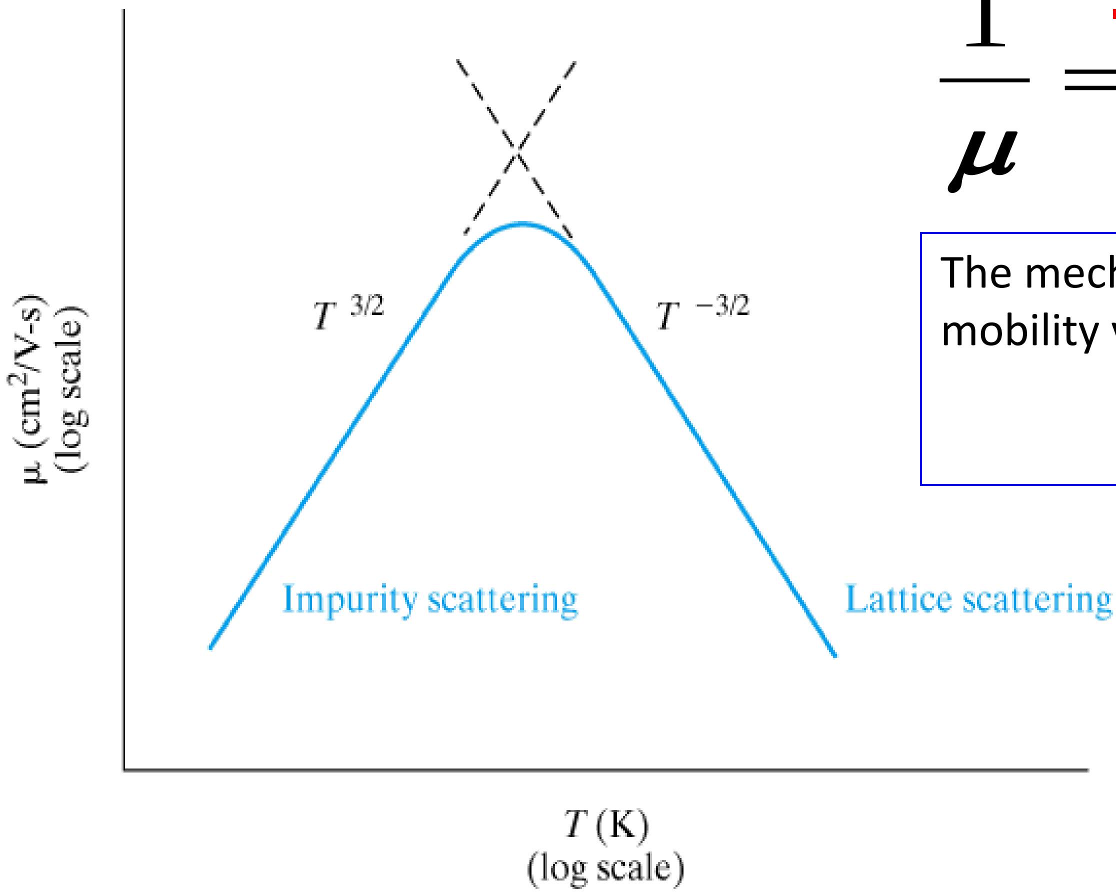
$\mu \quad \alpha \quad T^{-3/2}$ lattice scattering

$\mu \quad \alpha \; T^{3/2}$ impurity scattering



Mobility depends on doping. For Si at 300K:

Impurity & Lattice Scatterings



$$\frac{1}{\mu} = \frac{1}{\mu_I} + \frac{1}{\mu_\ell}$$

The mechanism causing the lower mobility value dominates !

Figure 3—21
Approximate temperature dependence of mobility with both lattice and impurity scattering.

Mobility vs. doped impurity concentration

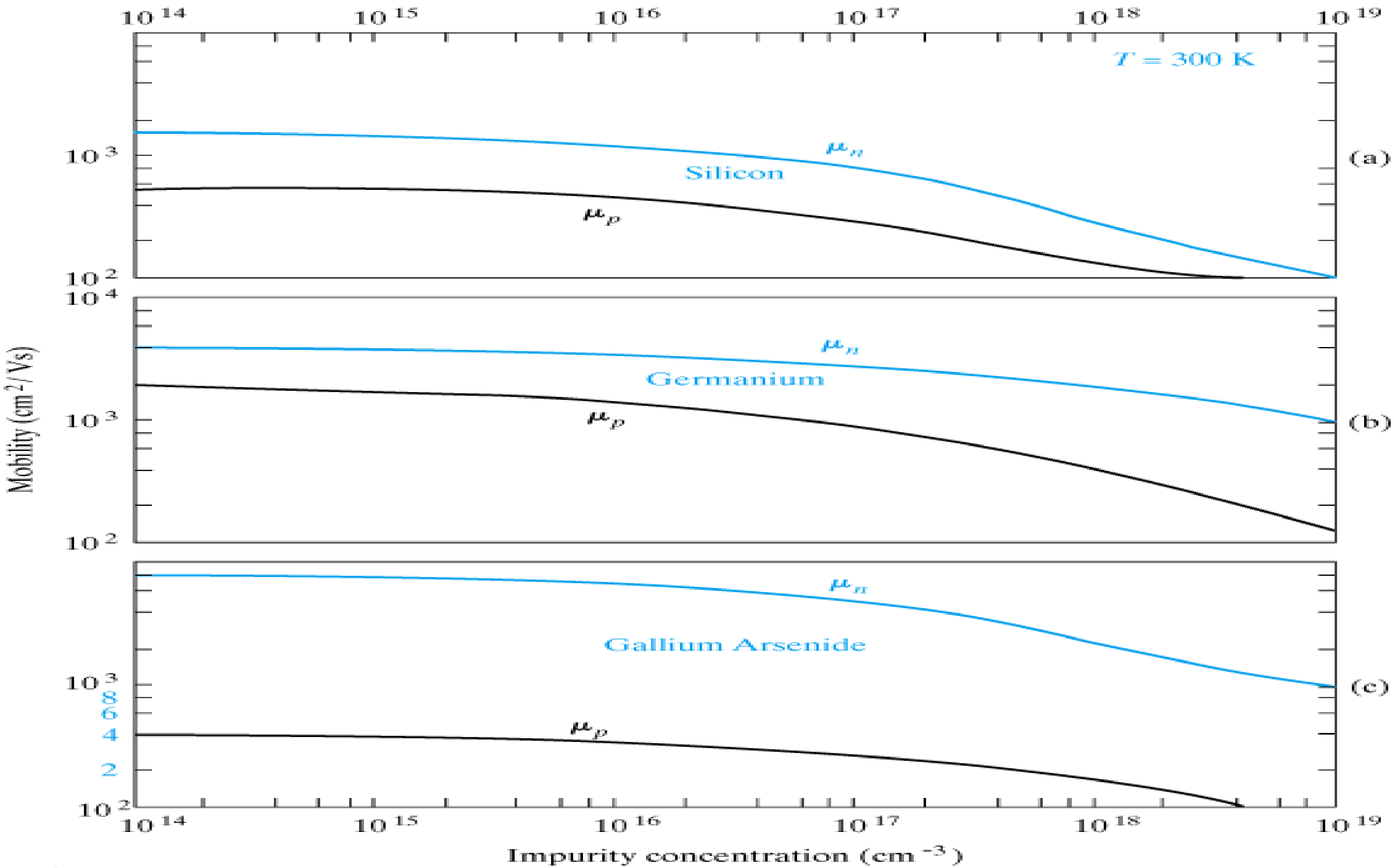


Figure 3—23

Variation of mobility with total doping impurity concentration ($N_a + N_d$) for Ge, Si, GaAs at 300 K.

Mobility vs. doped impurity concentration

Mobility is measure of *ease* of carrier drift:

- if $\tau_c \uparrow$, longer time between collisions $\rightarrow \mu \uparrow$
- if $m \downarrow$, "lighter" particle $\rightarrow \mu \uparrow$

- for low doping level, μ limited by collisions with lattice
- for medium and high doping level, μ limited by collisions with ionized impurities
- holes "heavier" than electrons:
  $\rightarrow$ for same doping level, $\mu_n > \mu_p$

High-Field Effects & Drift Velocity Saturation

For low electric fields, the Ohm's law is valid in the carrier drift process :

$$J_x = \sigma \varepsilon_x$$

(Usually valid for $\varepsilon_x < 10^3$ V/cm)

$$\sigma \neq f(\varepsilon_x)$$

$$J_x = -qnV_d$$

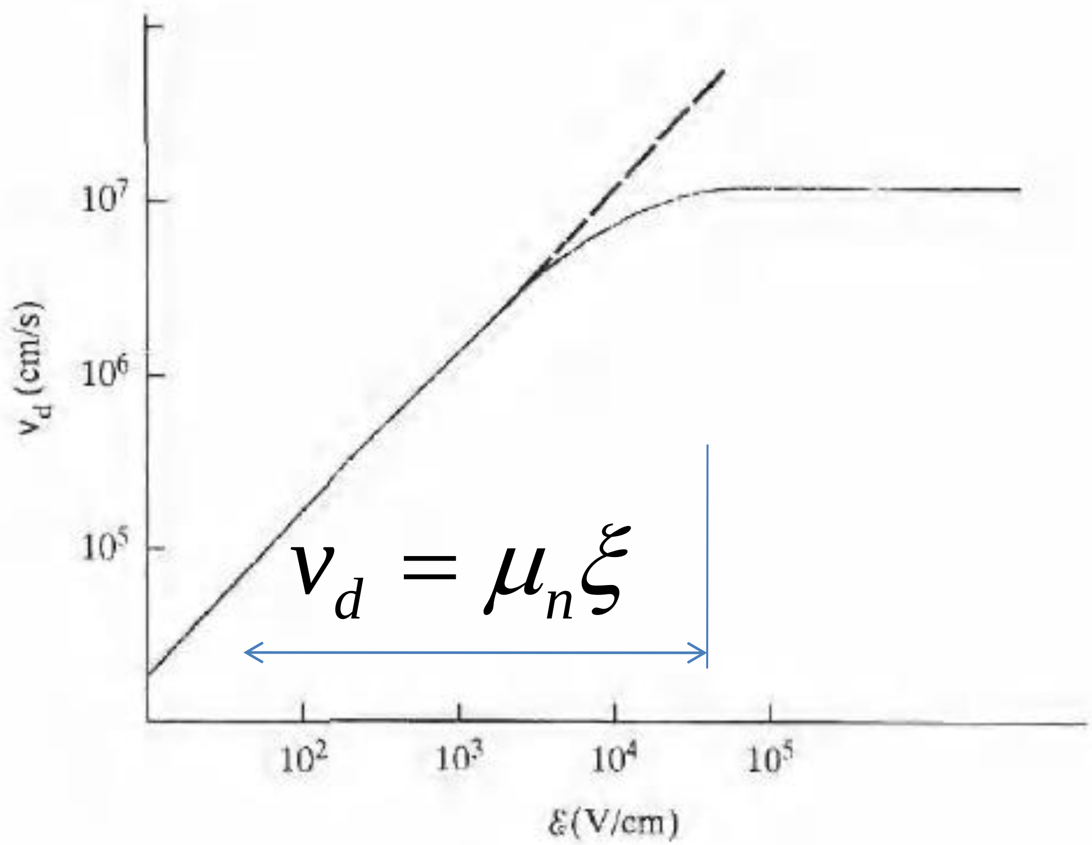
For high electric fields, <u>the drift velocity</u> (V_d) (*i.e.*, current density) exhibits a sublinear dependence on the electric field.

(Usually valid for $\varepsilon_x > 10^3$ V/cm)

$$V_d \cong 10^7 \text{ cm/s}$$

$$\sigma = f(\varepsilon_x)$$

Saturation of electron drift velocity at high electric field

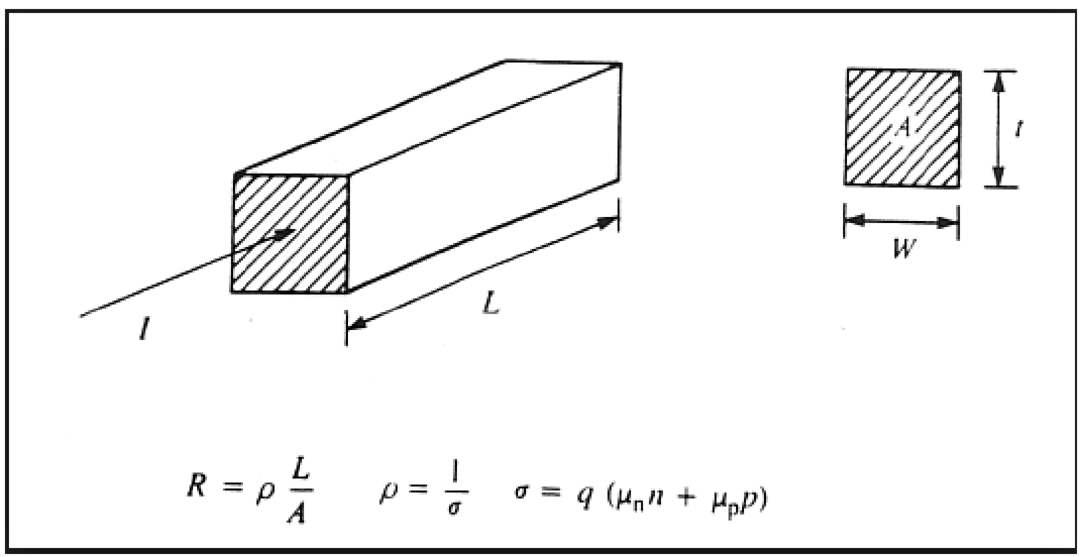


Electrical conductivity

- $\sigma_i = en_i(\mu_n + \mu_p)$ is the intrinsic conductivity of a semiconductor material
- For extrinsic semiconductors assuming complete ionization, $N_d or\ N_a \gg n_i$
- Hence the conductivity reduces to
- $\sigma_n \approx eN_d\mu_n\ and\ \sigma_p \approx e\ N_a\mu_p$ thus the conductivity is purely dependent on the majority carrier concentration

Electrical resistance

- $J = \sigma E = \sigma \frac{V}{L}$ where L is the length of the SC material
- $I = JA = \frac{\sigma V A}{L}$ and the elctrical resistance is given by
- $R = \frac{V}{I} = \frac{1}{\sigma}\frac{L}{A} = \frac{\rho L}{A}$



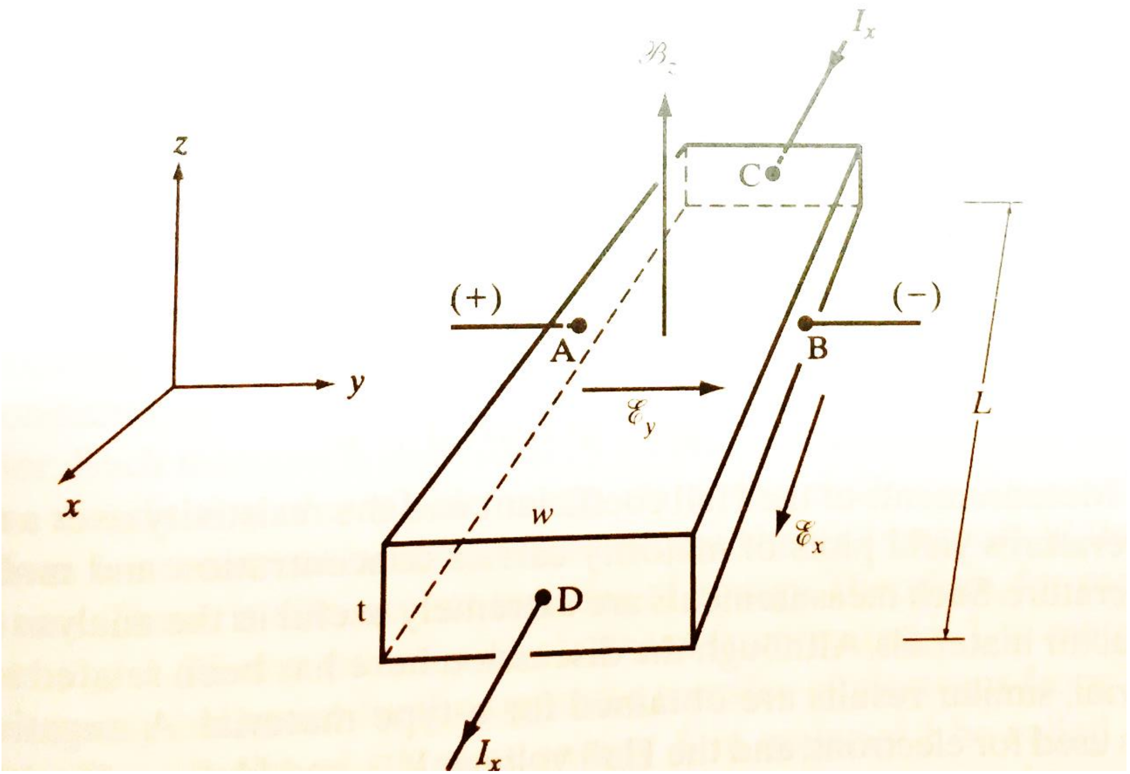
Electrical resistivity

- $\rho = \frac{1}{\sigma} = \frac{1}{e(n\mu_n + p\mu_p)}$ is the electrical resistivity
- Resistance, conductance, resistivity and conductivity, depend only on the majority carrier concentration and not on the minority carrier concentration

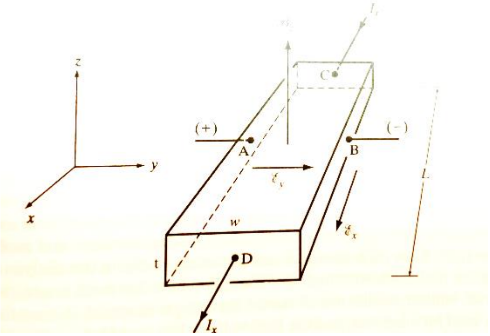
Hall effect

- Hall Effect was discovered by Edwin Hall in 1879.
- An important experiment to measure the carrier concentration and mobility of semiconductor devices

Hall experiment



Hall experiment



- A semiconductor device of Length L, width W and thickness t is placed in a magnetic and electric filed in x and z direction
- Current I_x flows in the +x-direction, a magnetic filed B_z is applied in the + z direction
- Assuming that material is p-type, holes are the majority carriers and take place in electrical conduction
- $J_x = \frac{I_x}{A}$ Assuming that the current is set by applying a Voltage $V_x, we\ have\ V_x = E_x L\ and\ \frac{V_x}{I_x} = R$

Hall experiment

- The magnetic field deflects the positive charges due to Lorentz force
- The charges are driven in the –y direction, thus the positive charges accumulate on one side of the material
- $F_y = qv\ x\ B = ev_x B_z$ where v_x is the drift velocity of the charge carriers in the +x direction
- $F_y = qE_y - q\ v_x B_z$
- Fy=0 only when $E_y = V_x B_z$
- $V_{AB} = E_y W$ → Hall Voltage
- $E_y = (Jx/qp_0)B_z = RH.\ JxBz$
- $R_H = 1/qp_0$ → Hall coefficient
-

  $P_0 = 1/R_H.q$
- $p = \frac{I_x B_z}{tqV_H}$

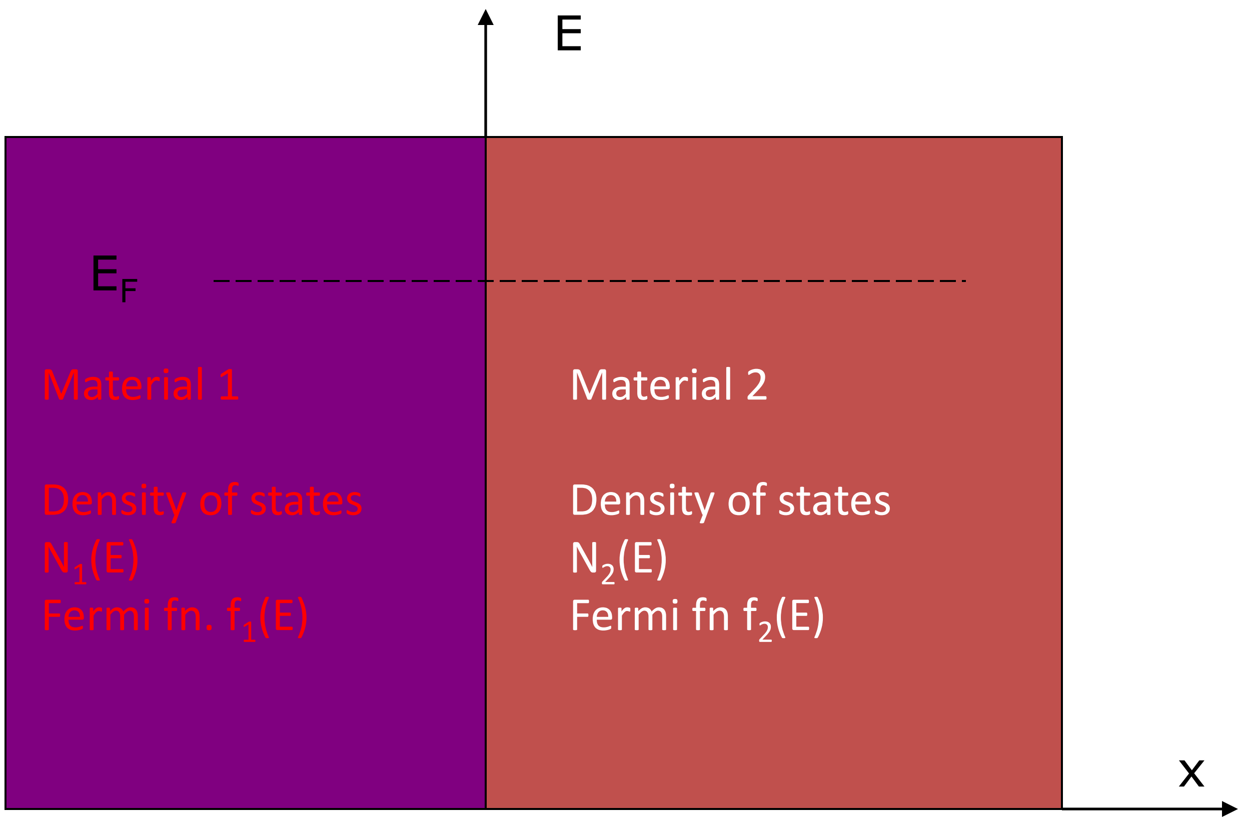
Determination of parameters

- Carrier concentration
  - $p = \frac{I_x B_z}{tqV_H}$ for p-type SC, the hall voltage polarity is positive
- This is one of the major applications of the Hall experiment as it helps in finding the material type by just looking at the hall voltage polarity
- The Hall voltage is positive for p-type and negative for n-type semicondcutors

Determination of parameters

- Carrier mobility
- $J_X = \frac{I_x}{A} = p\mu_p q E_x = \frac{p\mu_p q V_x}{L}$
- $\mu_p = \frac{I_x L}{qApV_x}$
- Similarly one repeat the same experiment for n-type semiconductors
- $n = \frac{I_x B_z}{t(-q)(-V_H)} = \frac{I_x B_z}{tqV_H}$ and $\mu_n = \frac{I_x L}{qAnV_x}$

Invariance of Fermi level at equilibrium



At energy **E**, the rate of transfer of electrons from **1** to **2** is proportional to the number of filled states at **E** in material 1 times the number of empty states at **E** in material 2 :

$$\propto \{N_1(E)f_1(E)\} \times \{N_2(E)[1 - f_2(E)]\}$$

$$\propto \{N_2(E)f_2(E)\} \times \{N_1(E)[1 - f_1(E)]\}$$

At equilibrium

$$\{N_1(E)f_1(E)\} \times \{N_2(E)[1 - f_2(E)]\} = \{N_2(E)f_2(E)\} \times \{N_1(E)[1 - f_1(E)]\}$$

$$N_1(E)f_1(E)N_2(E) = N_2(E)f_2(E)N_1(E)$$

$$f_1(E) = f_2(E) \quad \rightarrow$$

$$f_1(E) = \frac{1}{1+e^{(E-E_{F1})/kT}} = f_2(E) = \frac{1}{1+e^{(E-E_{F2})/kT}}$$

$$E_{F1} = E_{F2}$$

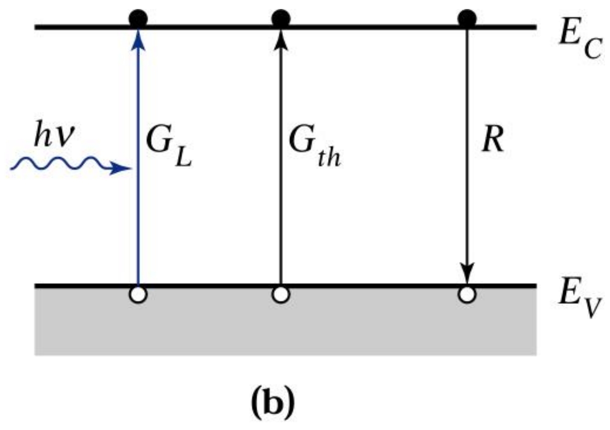
$$\frac{dE_F}{dx} = 0$$

This indicates that no gradient exists in the Fermi level at equilibrium !

Excess Carriers in Semiconductors

Objectives:

- Understanding how photons interact with direct and indirect band gap semiconductors
- Generation and recombination of excess carriers
- Quasi Fermi levels in equilibrium
- Diffusion current calculation
- Continuity equation



Direct generation and recombination of electron-hole pairs: (*a*) at thermal equilibrium and (*b*) under illumination.

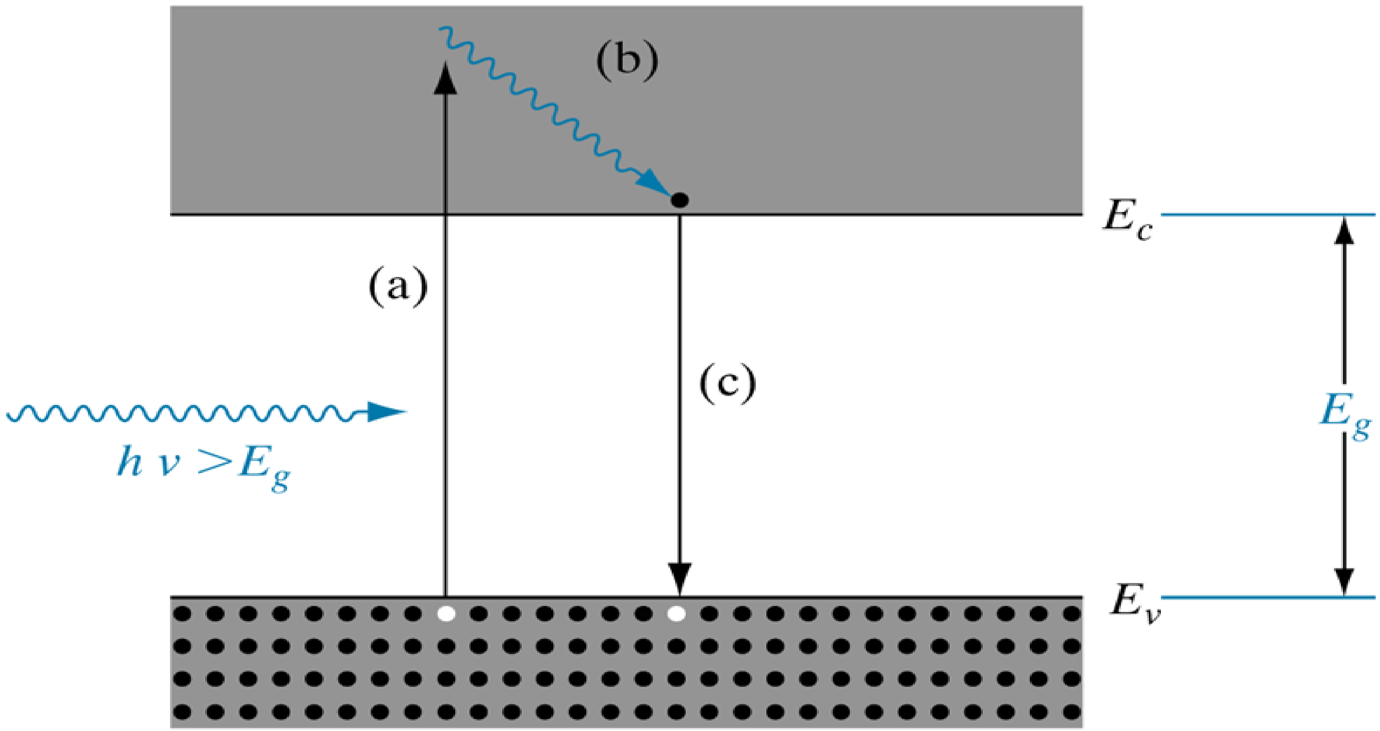


Figure 4—1

Optical absorption of a photon with $h\nu > E_g$:

(a) an EHP is created during photon absorption;

(b) the excited electron gives up energy to the lattice by scattering events;

(c) the electron recombines with a hole in the valence band.

Most semiconductor devices operate by the creation of charge carriers in excess of the thermal equilibrium values !

- **Band gap energy measurement using the absorption of incident photons** :

- Photons are absorbed in material when $h\nu \geq E_g$

- Photons are transmitted thru material when $h\nu \leq E_g$

$\Rightarrow$This explains why some materials are transparent in certain wavelength ranges !

- if E_g = ~2 eV : infrared/red parts of spectrum are transmitted.

- if E_g = ~3 eV : infrared/entire visible parts of spectrum are transmitted.

Optical absorption experiment

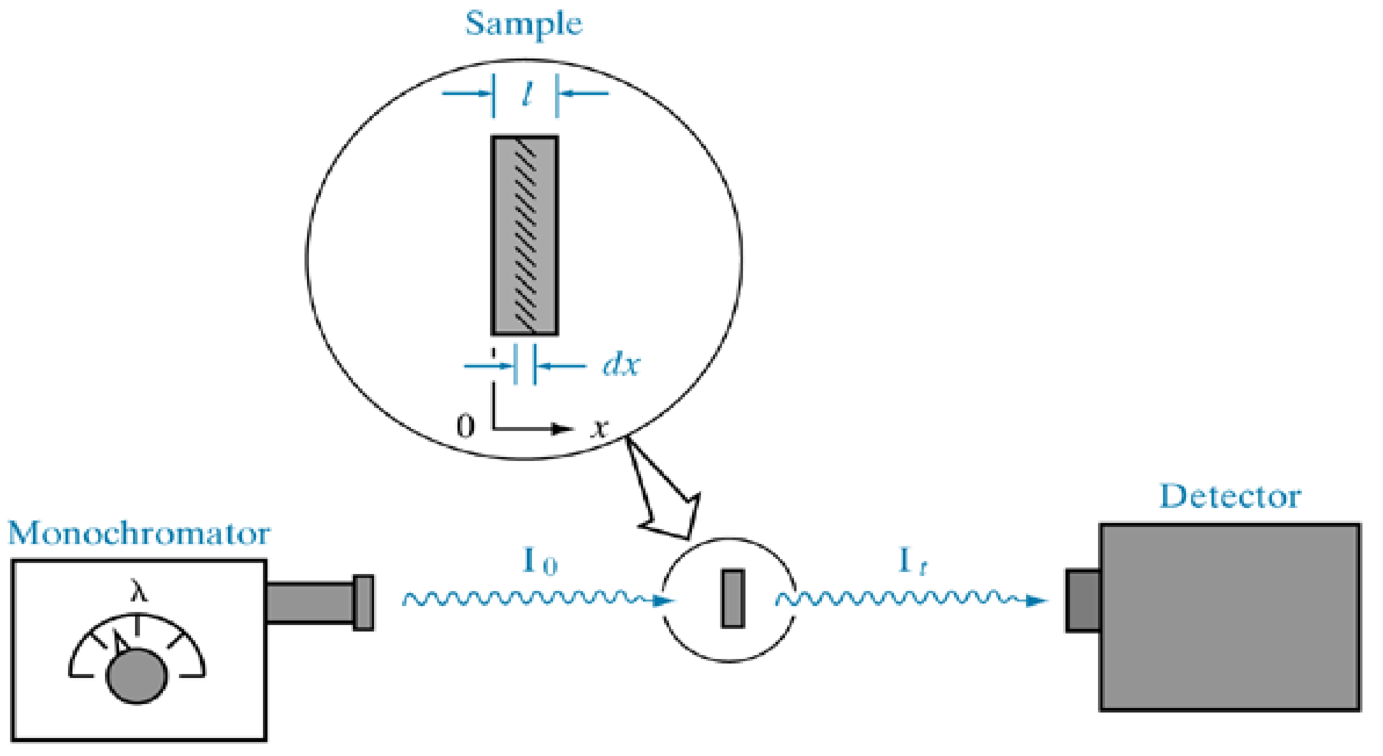


Figure 4—2
Optical absorption experiment.

When a beam of photons with $h\nu \geq E_g$ is incident on a Semiconductor wafer, some predictable amount of absorption can be determined by the properties of the material.

Ratio of **transmitted to incident light intensity** depends on the photon wavelength (λ) and sample thickness (l).

Let a photon beam of intensity I_0 (photons/cm^2-sec) is directed at a sample of thickness (l) with only photons of wavelength λ, selected by a monochromator.

The degradation of the intensity $-dI(x)/dx$ is proportional to the intensity remaining at x:

$$-\frac{dI(x)}{dx} = \alpha I(x) \Rightarrow I(x) = I_0 e^{-\alpha x}$$

The intensity of light transmitted through the sample thickness (l) is

$$I_t = I_0 e^{-\alpha l}$$

Optical absorption coefficient vs. wavelength of incident light

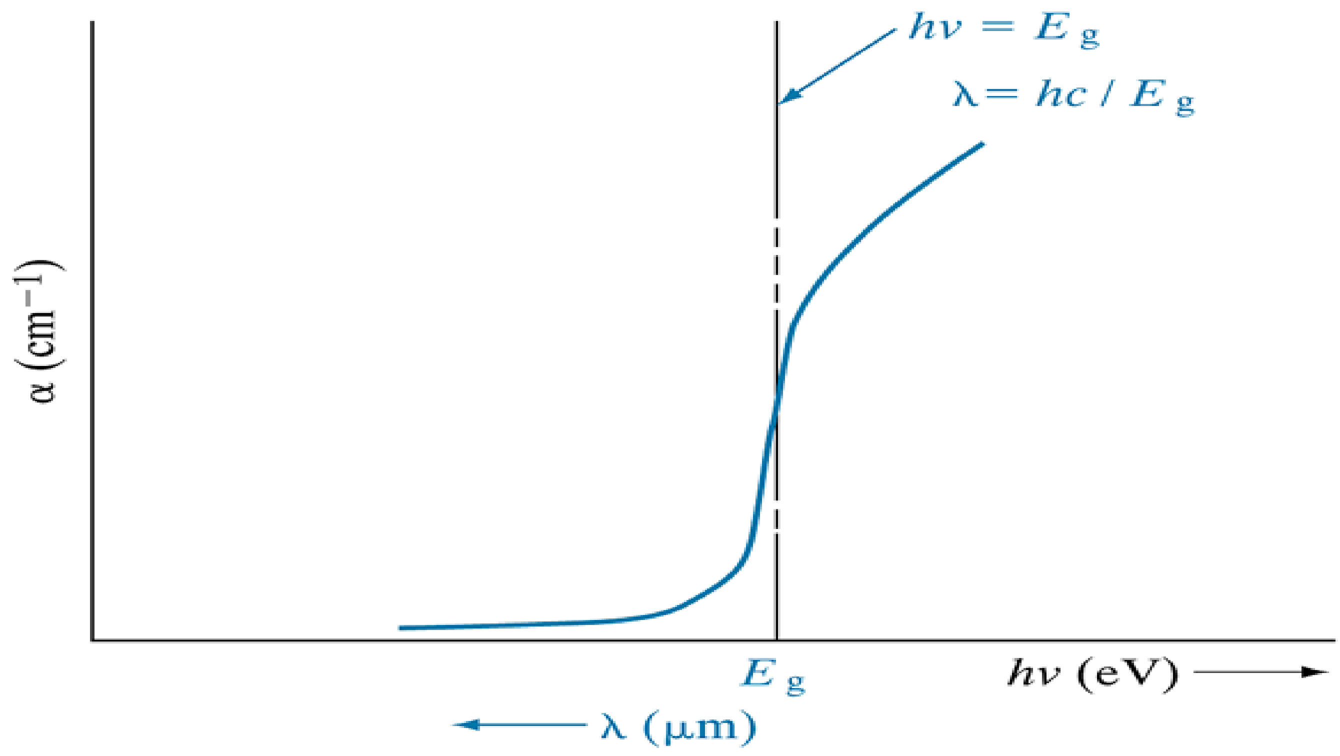


Figure 4—3
Dependence of optical absorption coefficient a for a semiconductor on the wavelength of incident light.

Semiconductors absorb photons with $h\nu \geq E_g$!

E (eV) = hc / λ (μm) =1.24/ ***λ***

- Si absorbs not only **its band gap light (~1μm)** but also **shorter wavelengths**, including those in the visible part of the optical spectrum.

- Si will be seen "**transparent**" in the most **infrared light spectrum** only (due to $h\nu \leq E_g$), but **not transparent** in **visible or ultraviolet light spectrum** (due to $h\nu \geq E_g$).

(***See Fig. 4-4***)

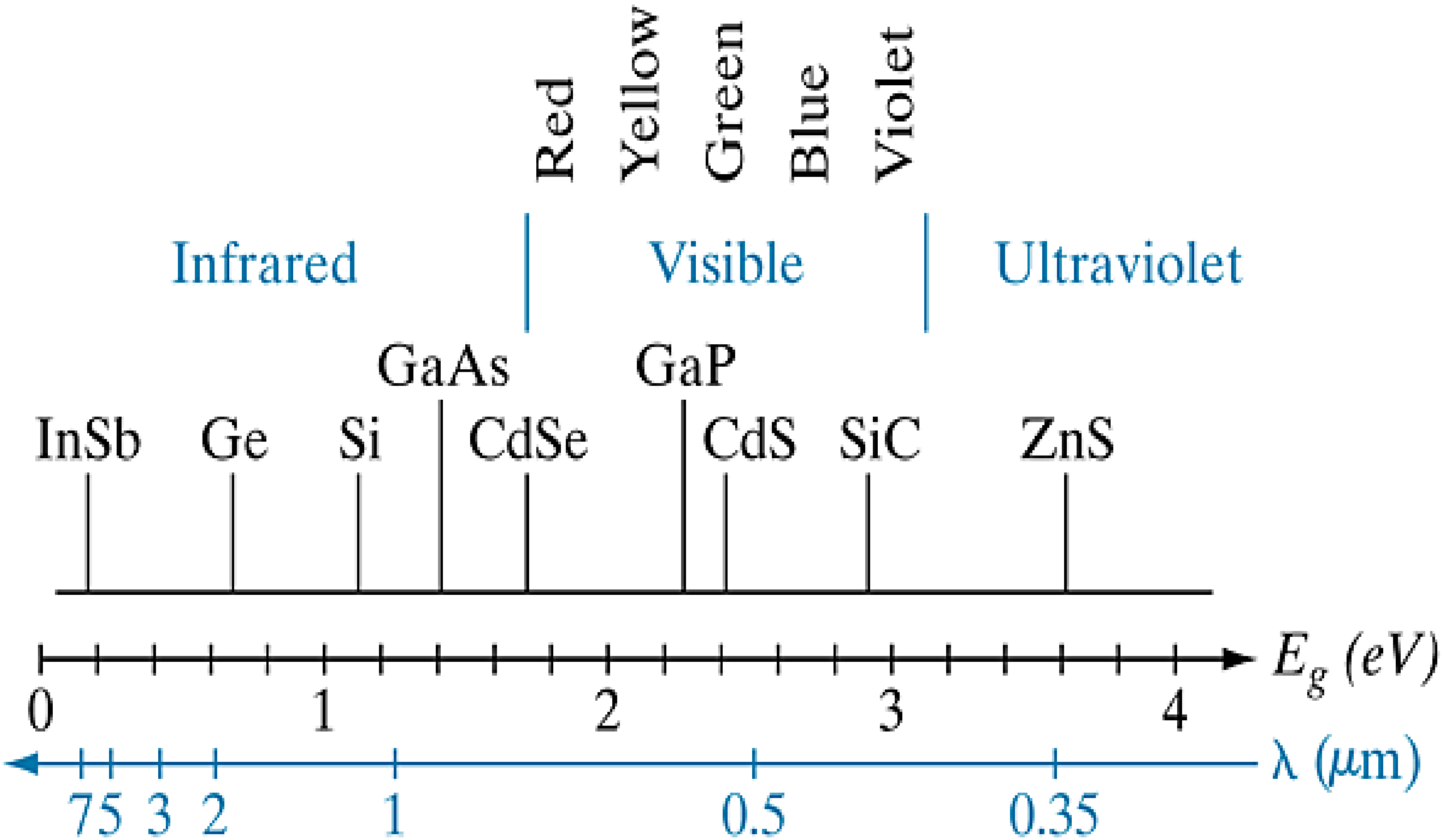


Figure 4—4
Band gaps of some common semiconductors relative to the optical spectrum.

Luminescence

When electron–hole pairs are generated in a semiconductor or when carriers are excited into higher impurity levels from which they fall to their equilibrium states light can be given off by the material.

The general property of light emission is called luminescence.

Photoluminescence

cathodoluminescence

electroluminescence

Excitation & recombination mechanisms in photoluminescence with a trapping level

Mean excitation time 10^{-8} sec or less

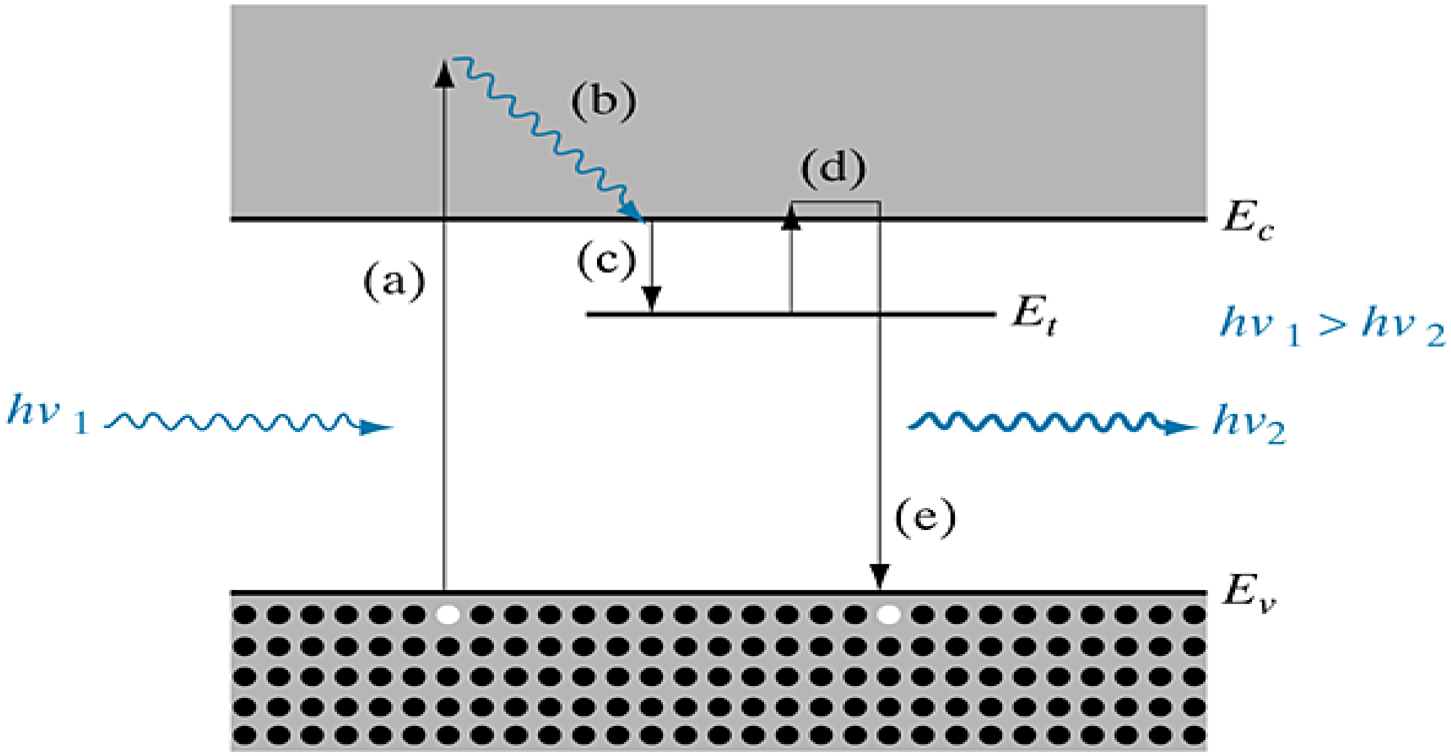


Figure 4—5
Excitation and recombination mechanisms in **photoluminescence** with a trapping level for electrons.

- The process where the lifetime of the EHP is 10^{-8} s is known as fluorescence---------direct recombination.

- When emission continues for seconds or minutes after the excitation source is removed--------------phosphorescence.

- If the trapping probability is greater than the probability of recombination, an electron makes several trips between the trap and conduction band before recombination.

- Many radiative transitions involve impurity levels within the band gap…..eg. ZnS