ECE 340: Semiconductor Electronics

Chapter 4: Excess Carriers in Semiconductors

Wenjuan Zhu

Outline

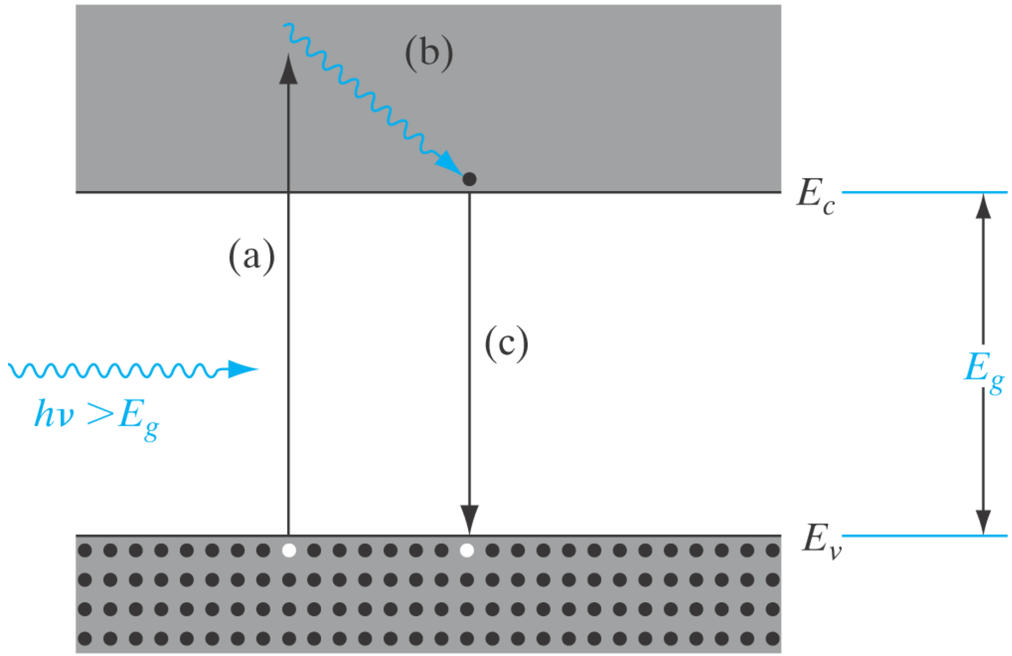
- Optical absorption
- Luminescence
- Carrier lifetime and photoconductivity
  - Direct recombination of electrons and holes
  - Steady state carrier generation; Quasi-Fermi levels
  - Photoconductive devices

Turn the light ON semiconductors

When we turn light on, we can generate excess electron-hole pairs (EHPs), depending on the light frequency (energy)

- If $h\nu \geq E_g$

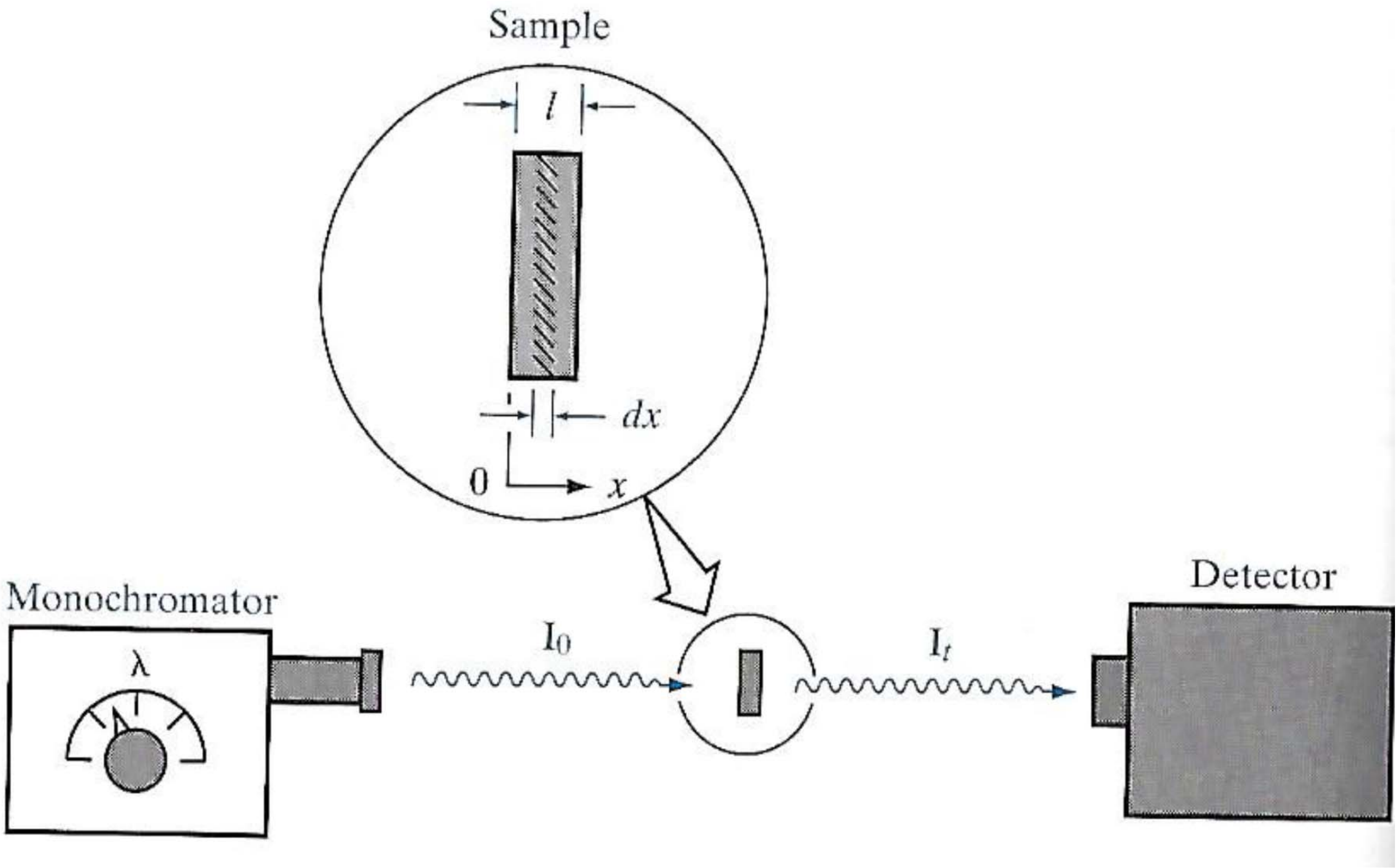
  photon can be absorbed, and generate EHP



- If $h\nu < E_g$

  no light absorption and EHP generation.

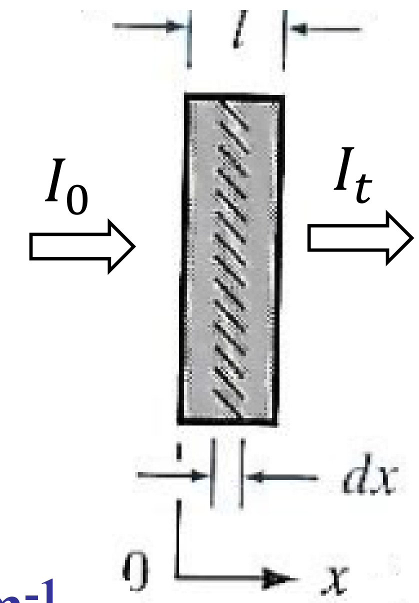
Optical absorption experiment



Transmitted light and absorption coefficient

- **Assume photon with $h\nu \geq E_g$, intensity I_0 , sample thickness l, then**

$$-\frac{dI(x)}{dx} = \alpha I(x)$$

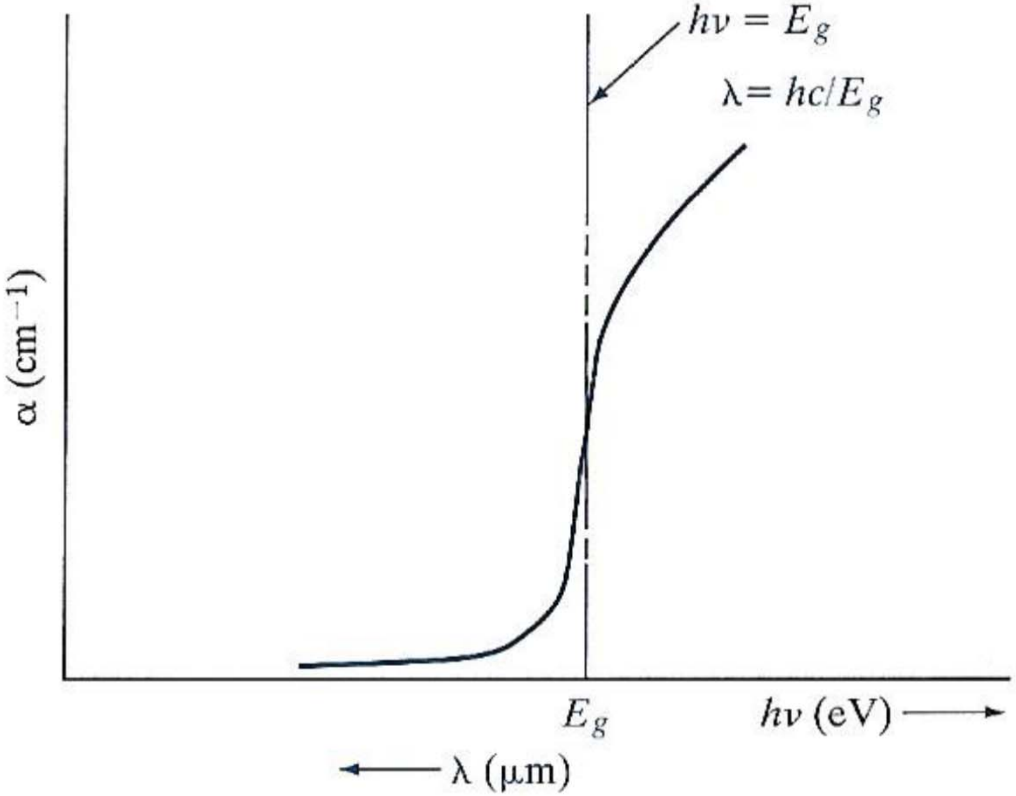


- **The intensity of transmitted photons is:**

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

where α is called absorption coefficient. Unit: cm^{-1}

Dependence of optical absorption on the wavelength of incident light

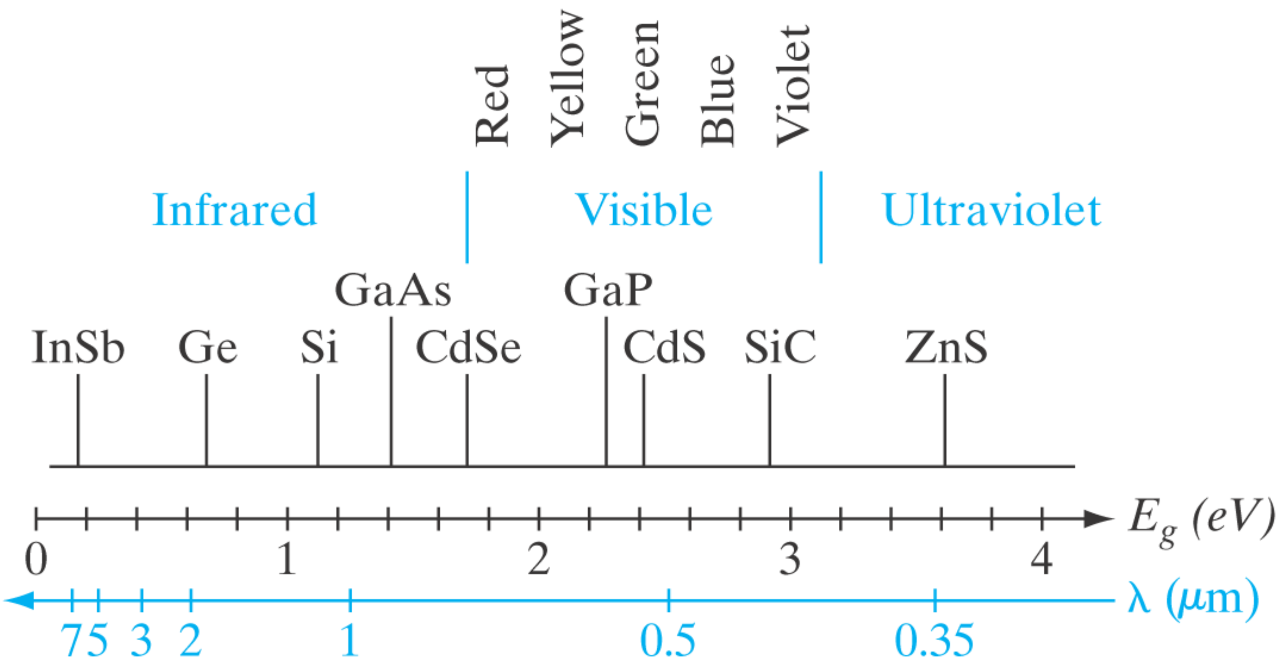


If E is in eV, and λ in μm, then

$$\lambda = \frac{1.24}{E}$$

- **A semiconductor absorbs photons with energies equal to or larger than the band gap.**

Band gaps of common semiconductors relative to the optical spectrum



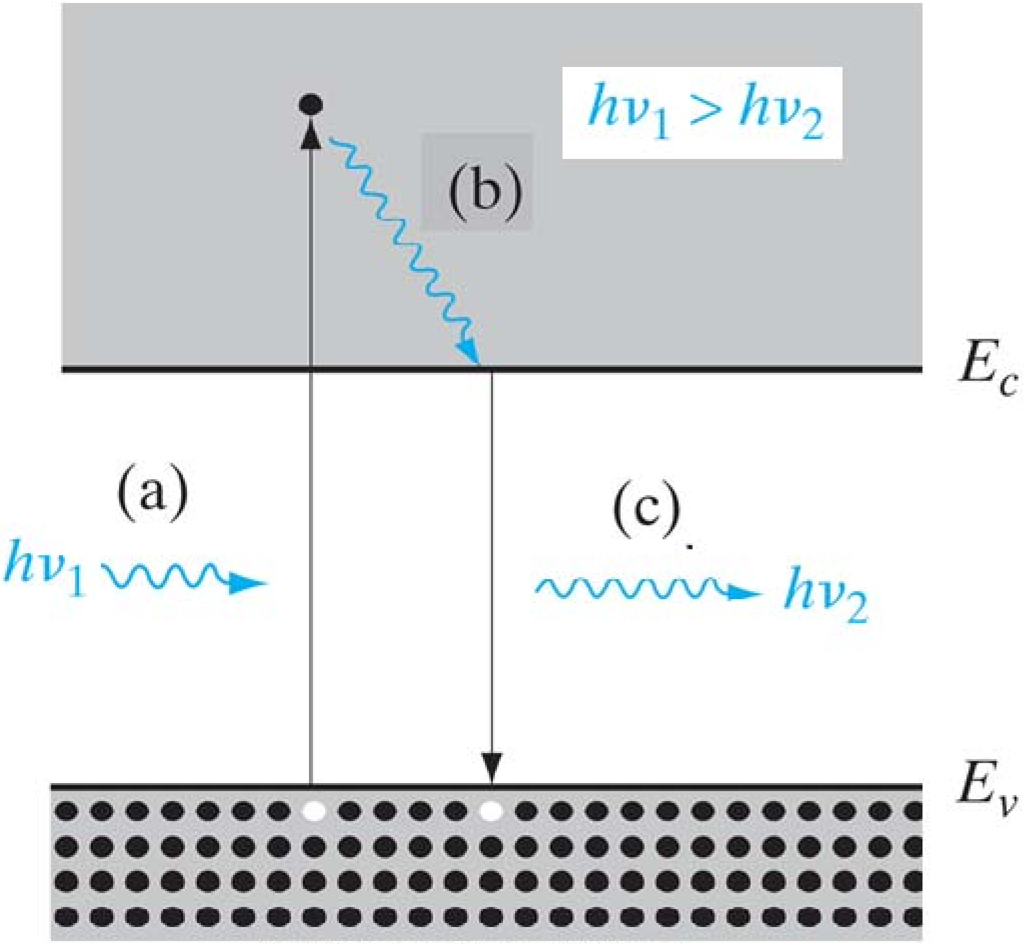
Outline

- Optical absorption
- Luminescence
- Carrier lifetime and photoconductivity
  - Direct recombination of electrons and holes
  - Steady state carrier generation; Quasi-Fermi levels
  - Photoconductive devices

Luminescence

- Luminescence: light emission resulting from recombination of the excited carriers.
- According to the excitation mechanism, there are different types of luminescence:
  - Photoluminescence: carrier are excited by photon absorption
  - Electroluminescence: carrier excitation occurs by the introduction of current into the sample

Photoluminescence



If $h\nu < E_g$, no light absorption

If $h\nu \geq E_g$, then

(a) Absorb photon with energy $h\nu_1$

(b) Give up extra kinetic energy $h\nu_1 - E_g$ to lattice as heat

(c) Recombination, release photon with energy E_g

Excess carrier

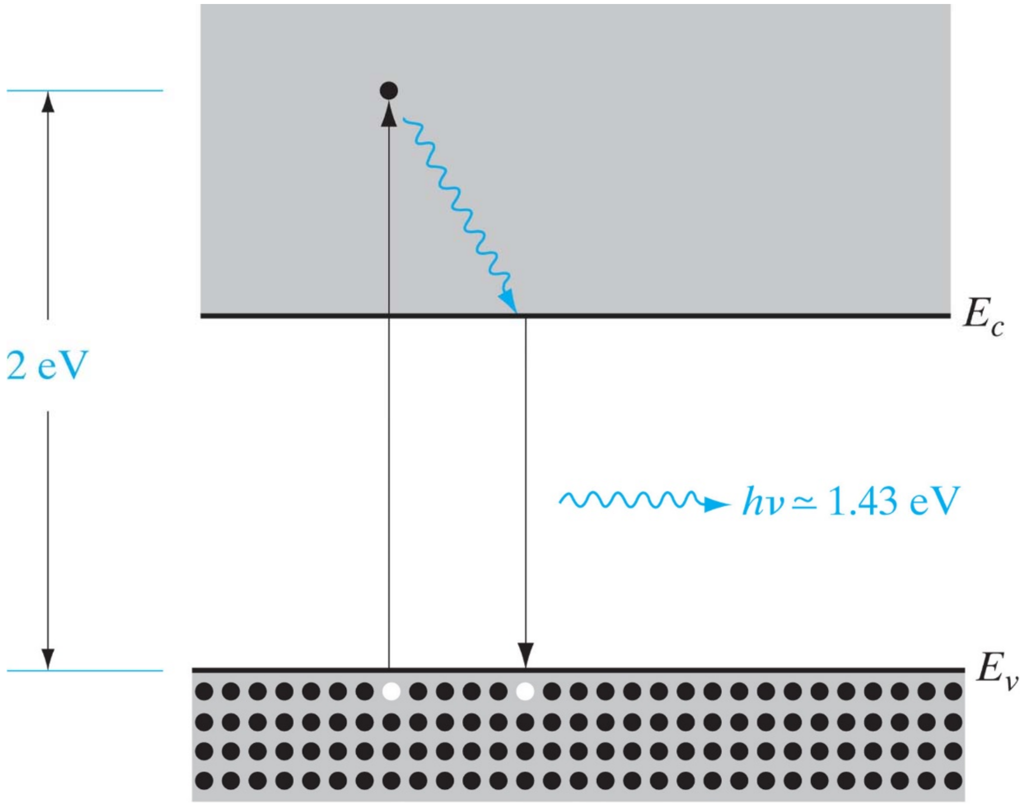
- Incident photon flux is the number of incident photons per unit time:

Incident light power (unit: watt =J/s)

$$\boldsymbol{\Phi = \frac{P_{op}}{h\nu}}$$

Photon energy (unit: J)

Example



A 0.46-um thick sample of GaAs is illuminated with monochromatic light of $h\nu$=2eV. The absorption coefficient α is $5\text{x}10^4\text{cm}^{-1}$. The power incident on the sample is 10mW.

(a) Find the total energy absorbed by the sample per second (J/s).

(b) Find the rate of excess thermal energy given up by the electrons to the lattice before recombination(J/s).

(c) Find the number of photons per second given off from recombination events, assuming perfect quantum efficiency.

Outline

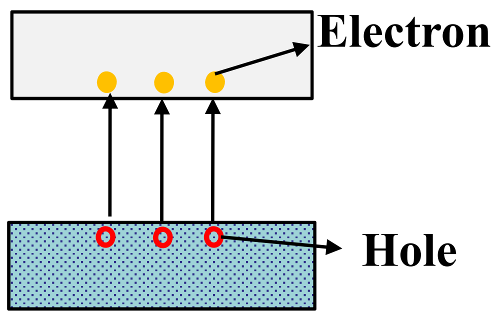
- Optical absorption
- Luminescence
- Carrier lifetime and photoconductivity
  - Direct recombination of electrons and holes
  - Steady state carrier generation; Quasi-Fermi levels
  - Photoconductive devices

Recall: Intrinsic material at thermal equilibrium

- **Recombination rate is determined by the number of electron and hole concentration:**

$$r_i = \alpha n_i^2$$

α is a constant



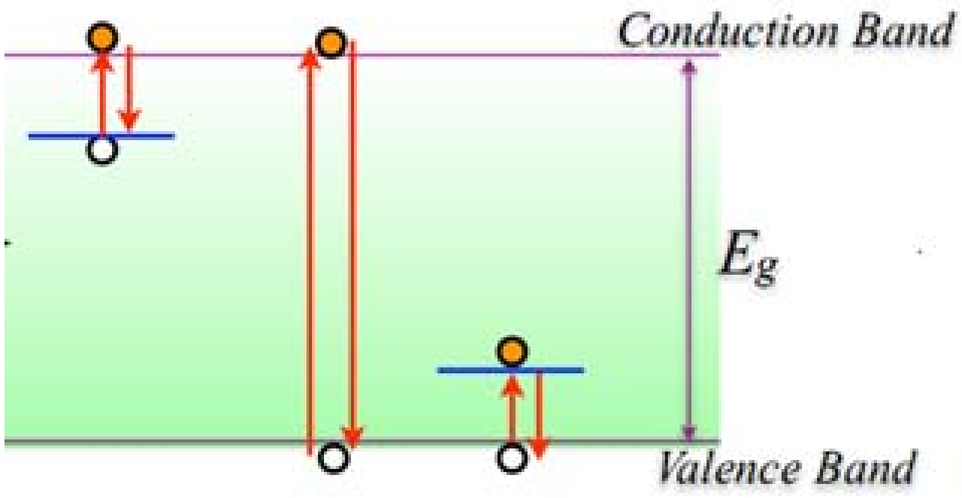
- **At equilibrium:**

$$g_i = r_i$$

$$\Rightarrow g_i = \alpha n_i^2$$

$$\boxed{n = p = n_i}$$

Extrinsic material at thermal Equilibrium



Generation rate = recombination rate

$$\alpha n_i^2 = \alpha n_0 p_0 \qquad\qquad n_0 p_0 = n_i^2$$

Shine light: recombination of electrons and holes

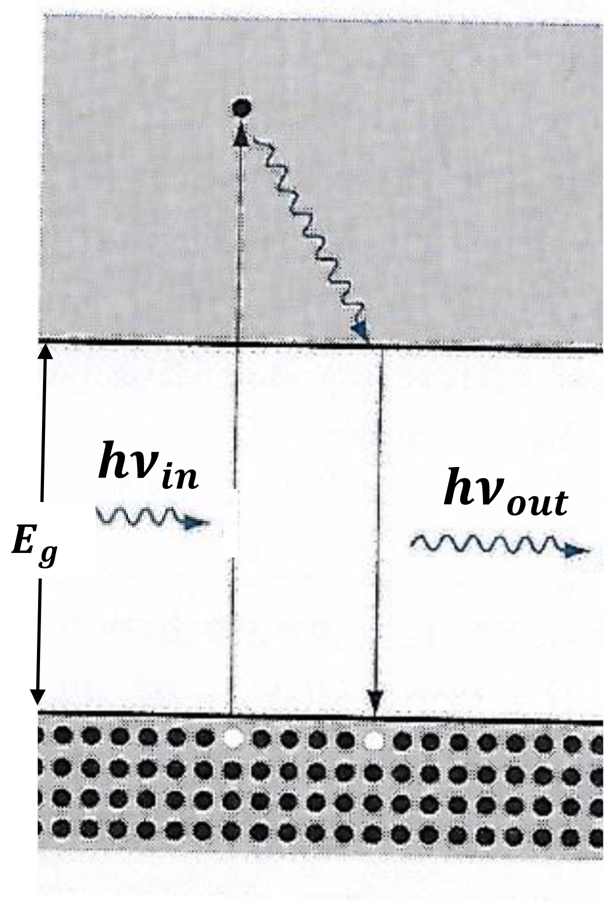
- Direct EHP recombination occurs spontaneously, emitting a photon of energy Eg

- Carrier concentration notation:

Equilibrium carrier concentration: n_0, p_0

Initial excess carrier concentration $\Delta n, \Delta p$.

Excess carrier concentration at any time: $\delta n(t), \delta p(t)$



Excess carrier concentration

- **The net rate of change in the conduction band electron concentration is:**

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

Generation rate **Recombination rate**

Generation rate is not equal to recombination rate at non-equilibrium condition!

Recall: at thermal equilibrium condition
generation rate = recombination rate ($\alpha_r n_i^2 = \alpha_r n_0 p_o$)

- **Assume at t=0, excess electron-hole population is created: Δn= Δp. The net rate of change in electron concentration is:**

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

- **Note $\boldsymbol{\alpha_r n_i^2 = \alpha_r n_0 p_0}$.**

For low level injection, $[\boldsymbol{\delta n(t)}]^2$ is very small.

If material is p type ($\boldsymbol{p_0 \gg n_0}$), then the rate of change is:

$$\frac{d\delta n(t)}{dt} = \alpha_r p_0 \delta n(t)$$

Excess carrier concentration

- **The excess carrier concentration:**

$$\delta n(t) = \Delta n e^{-\alpha_r p_0 t} = \Delta n e^{-t/\tau_n}$$

Where $\tau_n = (\alpha_r p_0)^{-1}$, electron recombination lifetime

- **If material is n type, the minority carrier is hole:**

$$\delta p(t) = \Delta p e^{-\alpha_r n_0 t} = \Delta p e^{-t/\tau_p}$$

$where\ \ \tau_p = (\alpha_r n_0)^{-1},$ hole recombination lifetime

- **More generally:**

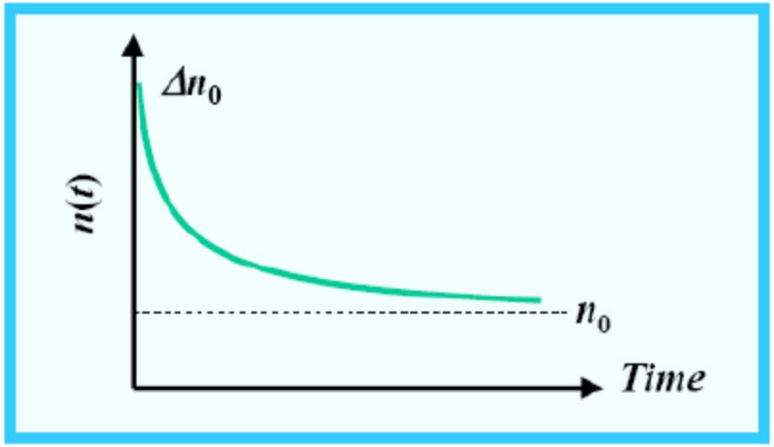
$$\tau = \frac{1}{\alpha_r (n_0 + p_0)}$$

Total carrier concentration

- Electron and hole concentration as a function of time

$$\boxed{n(t) = n_0 + \Delta n e^{-t/\tau_n}}$$

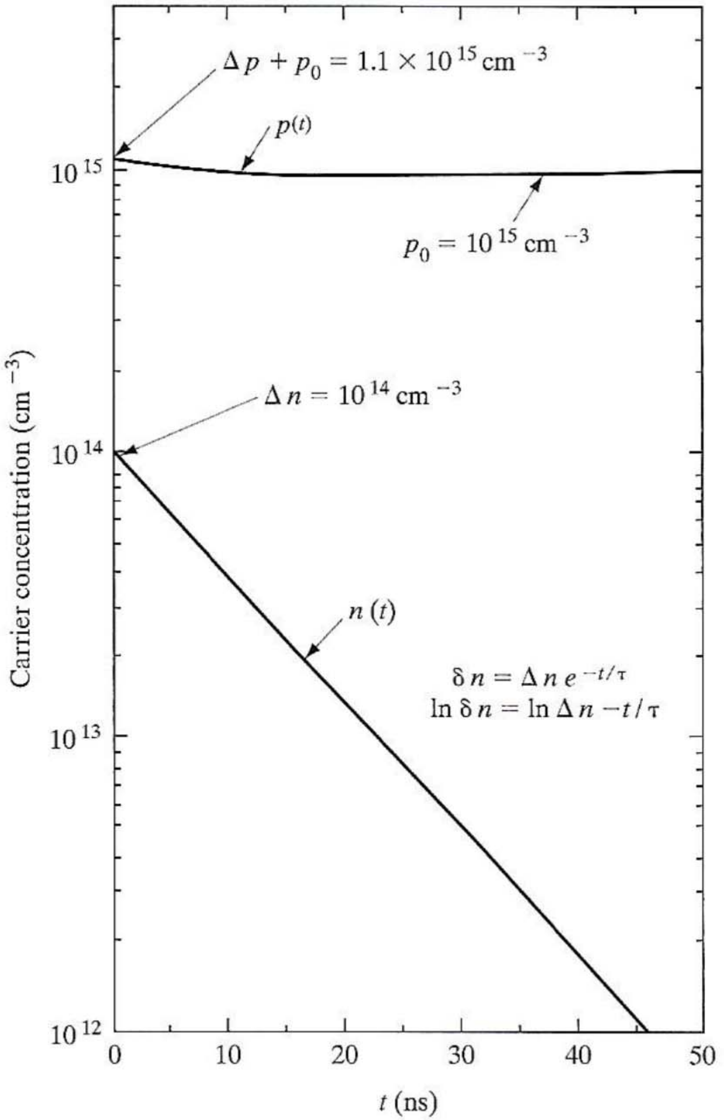
$$\boxed{p(t) = p_0 + \Delta p e^{-t/\tau_p}}$$



Example 1

- Assume a sample of GaAs is doped with $10^{15} acceptors/cm^3$. The intrinsic carrier concentration of GaAs is approximately $10^6 cm^{-3}$, Now if $10^{14} EHP/cm^3$ are created at t=0, carrier recombination lifetime is $\tau_n = \tau_p = 10^{-8} s$. Find out the electron and hole carrier concentration as a function of time.

Decay of excess electrons and hole by recombination



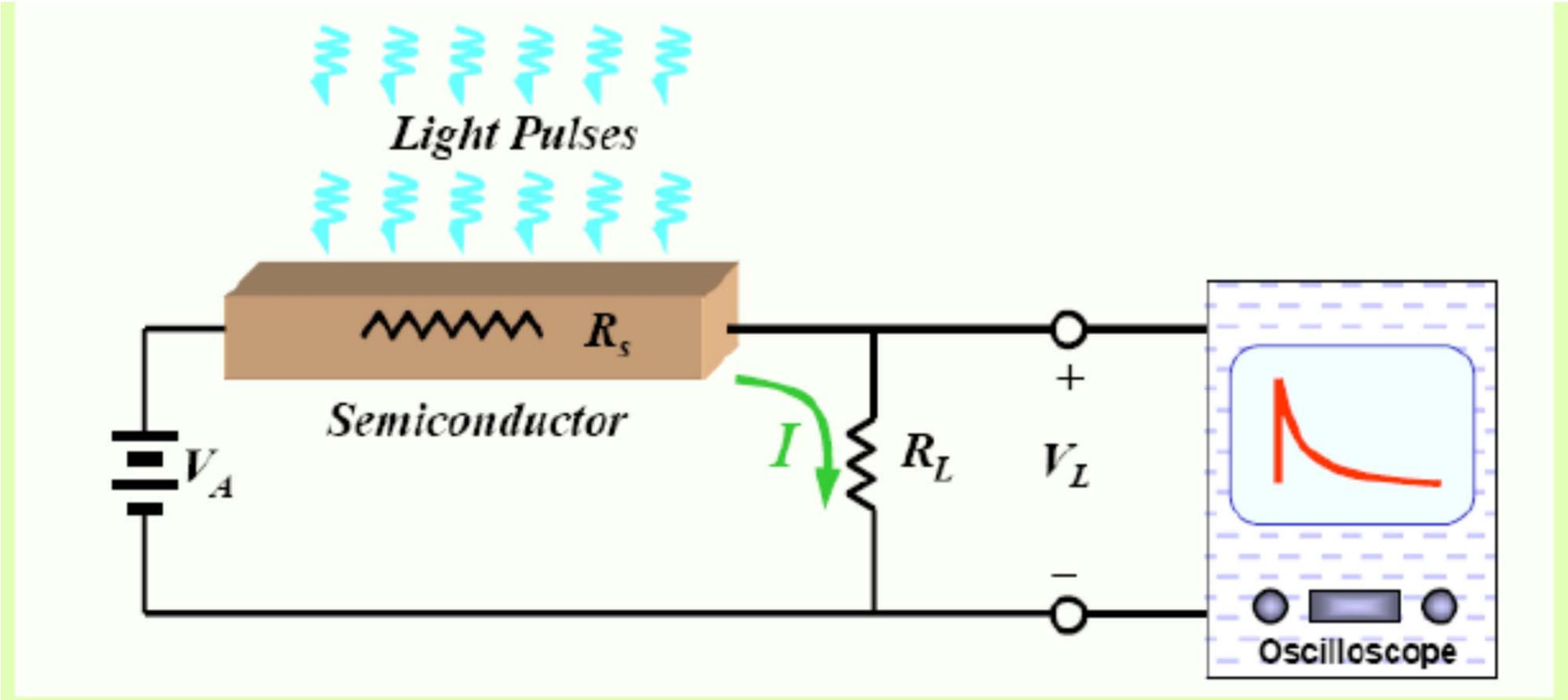
In p type material:

$$p_0 > n_0 \quad \text{and} \quad \Delta n = \Delta p$$

$$\Rightarrow \frac{\Delta \mathrm{p}}{p_0} < \frac{\Delta n}{n_0}$$

- **Minority carrier concentration: large percentage change**
- **Majority carrier concentration: small percentage change**

Experiment setup for photoconductivity and recombination lifetime measurement



Outline

- Optical absorption
- Luminescence
- Carrier lifetime and photoconductivity
  - Direct recombination of electrons and holes
  - Steady state carrier generation; Quasi-Fermi levels
  - Photoconductive devices

Steady state carrier generation

- At thermal equilibrium:

$$g(T) = \alpha_r n_i^2 = \alpha_r n_0 p_0$$

- If a steady light is shone on the sample,

$$g(T) + g_{op} = \alpha_r np = \alpha_r (n_0 + \delta n)(p_0 + \delta p)$$

Thermal generation rate   Optical generation rate   **Recombination rate**

- For steady state recombination and no trapping, $\Delta n = \Delta p$, then

$$\cancel{g(T)} + g_{op} = \cancel{\alpha_r n_0 p_0} + \alpha_r (n_0 + p_0)\delta n + \cancel{\delta n^2}$$

Excess carrier concentration

- For low level injection ($\delta n^2$is small), then:

$$g_{op} = \alpha_r(n_0 + p_0)\delta n = \frac{\delta n}{\tau}$$

- The excess carrier concentration:

$$\boxed{\delta n = \delta p = g_{op}\tau}$$

Quasi-Fermi Level

- At thermal equilibrium, carrier concentration is expressed by Fermi level:

$$n = n_i e^{(E_F - E_i)/kT}$$

$$p = p_i e^{(E_i - E_F)/kT}$$

- At steady state, the carrier concentration can be written in similar form by defining separate quasi-Fermi levels:

$$\boxed{n = n_i e^{(F_n - E_i)/kT}}$$

$$\boxed{p = p_i e^{(E_i - F_p)/kT}}$$

F_n: quasi-Fermi level for electron

F_p: quasi-Fermi level for hole

Example

- Assume that 10^{13} EHP/cm^3 are created optically every microsecond in a Si sample with $n_0=10^{14}$cm^{-3} and $\tau_n = \tau_p = 2\mu s$. Where is the quasi-Fermi level F_n and F_p?

Quasi-Fermi level and carrier concentration

	Thermal equilibrium carrier concentration n_0, p_0	**Excess carrier concentration** $\Delta n, \Delta p$	**Percentage change in carrier concentration** $\Delta n/n_0, \Delta p/p_0$	**Derivation of quasi-Fermi level from equilibrium Fermi level** $F_n - E_i, E_i - F_p$
Majority carrier	High	same	Small	Small
Minority carrier	**Low**	**same**	**Large**	**Large**

- At equilibrium:

$$F_n = F_p = E_F$$

Example

A semiconductor sample is illuminated with a steady state laser beam characterized by a photon energy of 1eV and an intensity of 10 mW. The semiconductor has a cross section $A=10^{-2}cm^2$ and a thickness of 1μm. The minority carrier lifetime is τ=10 ns.

a) By assuming the intensity of the transmitted light is negligible, compute the photon absorption rate (number of photons absorbed/sec)?
b) If each photon produces an electron-hole pair (EHP), compute the optical generation rate?
c) What is the concentration of excess minority carrier?

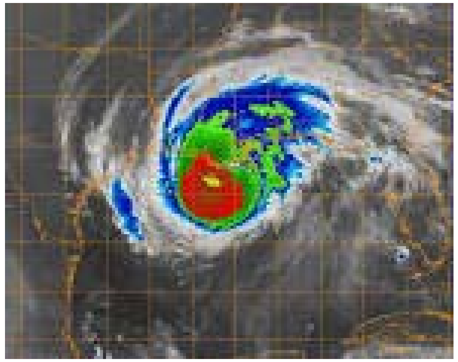
Outline

- Optical absorption
- Luminescence
- Carrier lifetime and photoconductivity
  - Direct recombination of electrons and holes
  - Steady state carrier generation; Quasi-Fermi levels
  - Photoconductive devices

Application of photodetectors

Digital camera

Street light

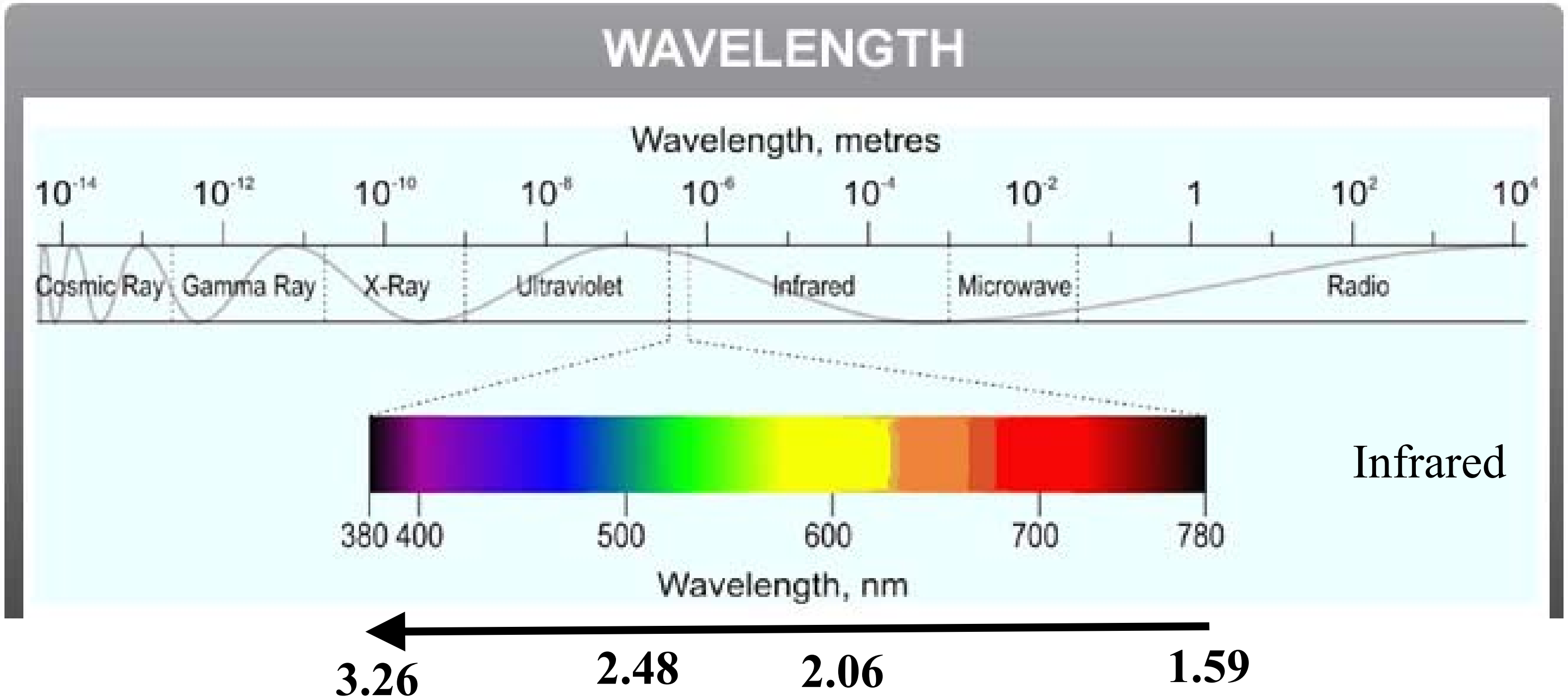


Infrared Satellite

Automatic door
Automatic door

Night vision camera

Semiconductor materials for photodetectors



Photon energy (eV)

SiC	CdS	CdSe	GaAs	Ge
2.86eV	2.42eV	1.73eV	1.43eV	(0.67eV)

- **Semiconductor are most sensitive to photons with energies equal to the band gap or slightly more energetic than band gap.**

Photoconductivity of a photodetector

- Under steady state light illumination, the excess carrier concentration is:

$$\delta n = g_{op}\tau_n \qquad \delta p = g_{op}\tau_p$$

- The conductivity change due to the light, called photoconductivity is:

$$\Delta\sigma = \underbrace{\sigma}_{\text{With light}} - \underbrace{\sigma_0}_{\text{Without light}} = q(\delta n \mu_n + \delta p \mu_p)$$

$$\Rightarrow \Delta\sigma = q g_{op}(\tau_n \mu_n + \tau_p \mu_p)$$