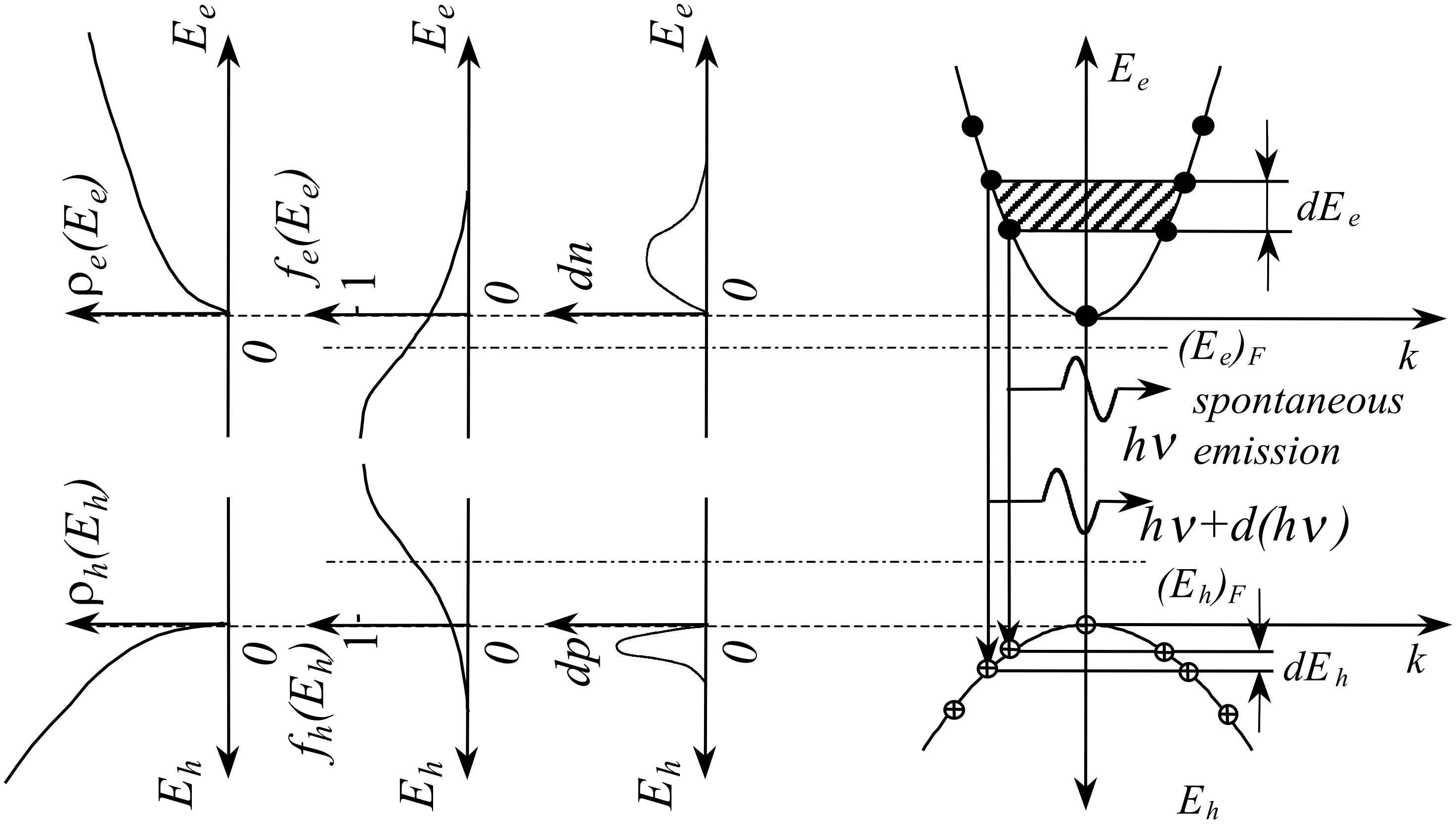
Recombination of carriers

Radiative recombination



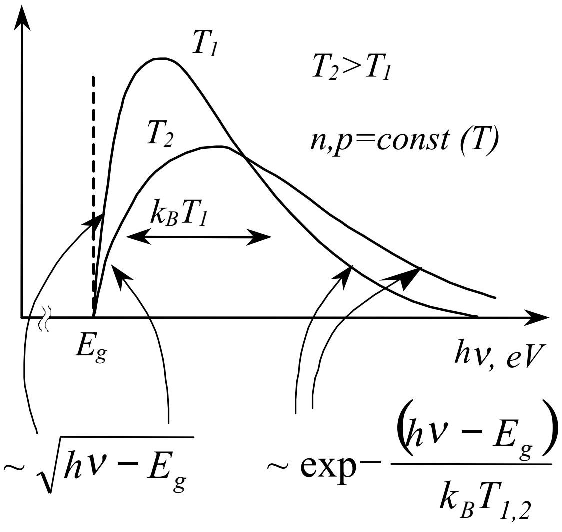
Transition of electrons with emission of photons

Recombination of carriers

Radiative recombination. Spontaneous emission spectrum.

Spectral dependence of the spontaneous emission intensity

$$\frac{d^2S}{d(h\nu)dt}, \frac{\text{quantum}}{\text{cm}^3 \cdot \text{sec} \cdot \text{eV}}$$



The number of photons $d^2S/dh\nu dt$ emitted per unit time, volume and energy interval is:

$$\frac{d^2S}{d(h\nu)dt} \sim \left[w^{\nu}_{c\to v} \cdot f_e(E_e(k)) \cdot f_h(E_h(k)) \cdot \rho(k)\right] \cdot \nu^2 \quad \frac{\text{quantum}}{\text{cm}^3 \cdot \text{sec} \cdot \text{eV}}$$

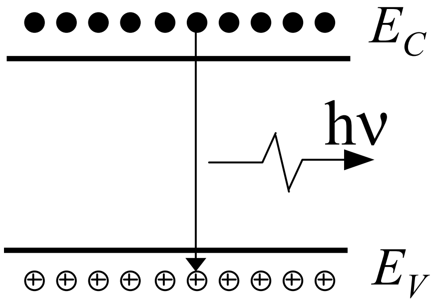
photon density of states

$\rho(k)$ – combined density of states; ν^2 is proportional to the density states of photons, $w^{\nu}_{c\to v}$ – the probability of transmission due to interaction with electromagnetic wave (weakly depends on ν), f_e, f_h – the distribution functions for electrons and holes, the $d^2S/dh\nu$ depends only on ν because $\mathbf{k}=\mathbf{k}(\nu)$.

$$\rho(k) \sim \sqrt{h\nu - E_g}, \quad f_e \cdot f_h \sim n \cdot p \cdot \exp - \frac{(h\nu - E_g)}{k_BT}$$

Recombination of carriers

Radiative recombination



The full number of emitted quantum is:

$$\overset{\text{full probability}}{R_\nu} = \underset{\text{full energy}}{\int_{h\nu=E_g}^{\infty}} \frac{d^2 N_\nu}{d\nu dt} d\nu = Bnp \quad n \cong p \quad R_\nu = Bn^2$$

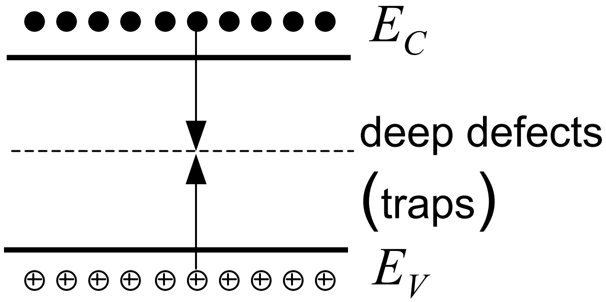
Under high level injection, when $n \cong p$ the number of emitted quantum per second is equal to the number of recombined electron-hole pairs per second:

$$R_\nu = \frac{n}{\tau_\nu}; \quad \tau_\nu = \frac{1}{Bn}$$

where τ_ν is the radiative lifetime of carriers.
In InGaAsP material for 1,3μm light – emitting diodes at T=300K
B is approximately 10^{-9}cm^3/s

Recombination of carriers

Recombination on defects or traps



Energy of electrons and holes is transferred to the lattice (so called phonon assisted processes).

Under condition $N_t >> n, p$ (N_t – trap concentration):

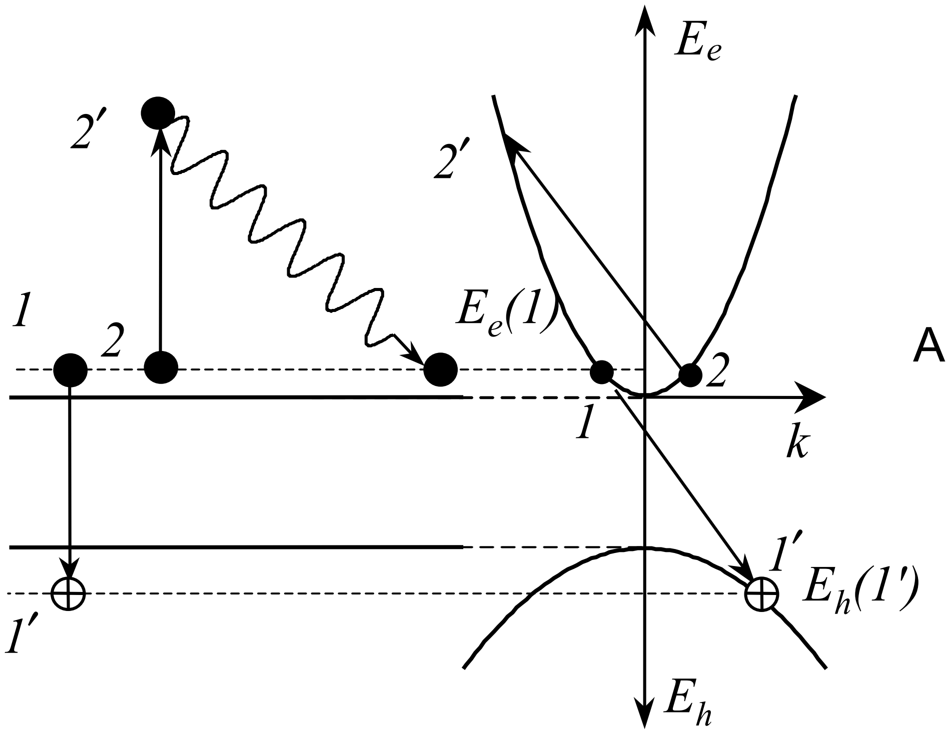
$$R_d = A \cdot n\,, \quad R_d = \frac{n}{\tau_d}\,, \quad \tau_d = \frac{n}{R_d} = \frac{1}{A}\,, \quad A = \upsilon \cdot \sigma \cdot N_t$$

where υ is velocity of carriers, σ is the capture cross section of the trap, $\mathbf{N_t}$ is density of traps. Usually in InGaAsP material $\boldsymbol{\tau_d}$ ~ 10^{-7}-10^{-8} sec.

Recombination of carriers

Auger recombination

A. Energy is transferred to electron



$$R_A \sim n(1) \cdot p(1') \cdot n(2)$$

At high level of injection **n** ≅ **p**

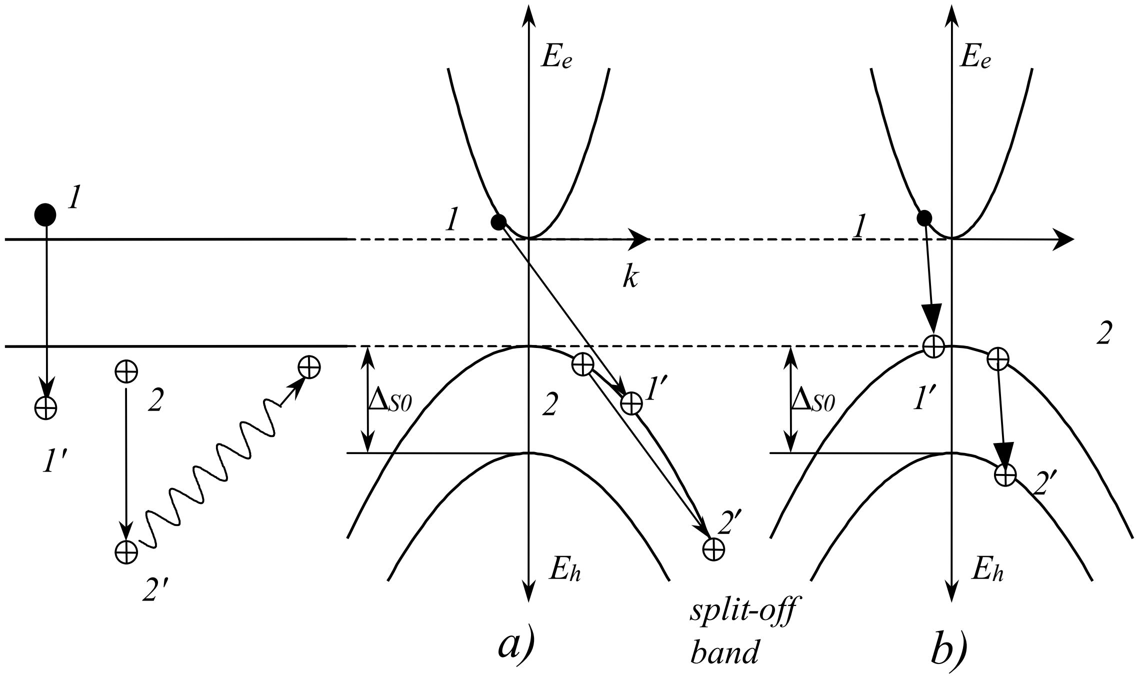
$$R_A = C \cdot n^3, \left[\frac{1}{\mathrm{cm}^3\mathrm{sec}}\right]$$

The energy $E_e(1)+E_g+E_h(1')$ is transferred to electron (2). Then hot electron in state $(2')$ transfer its energy to the lattice due to emission of photons.

Recombination of carriers

Auger recombination

B. Energy is transferred to hole



$$R_A \sim n(1) \cdot p(1') \cdot p(2)$$

$$n \approx p \Rightarrow R_A = C \cdot n^3$$

$$R_A = n / \tau_A$$

carrier lifetime – $\tau_A = (Cn^2)^{-1}$

In InGaAsP (1.3μ, 300K): $C \approx 3 \cdot 10^{-29} \mathrm{cm}^6/\mathrm{s}$

The energy $E_e(1) + E_g + E_h(1')$ is transferred to hole *(2)*. If E_g is approximately equals to the energy of spin-orbit splitting Δ_{S0} , Auger process *(b)* is more effective, then process *(a)*.

Recombination of carriers

Conclusion

$$R = A \cdot n + B \cdot n^2 + C \cdot n^3, \quad \left[\frac{1}{cm^3 s}\right]$$

traps

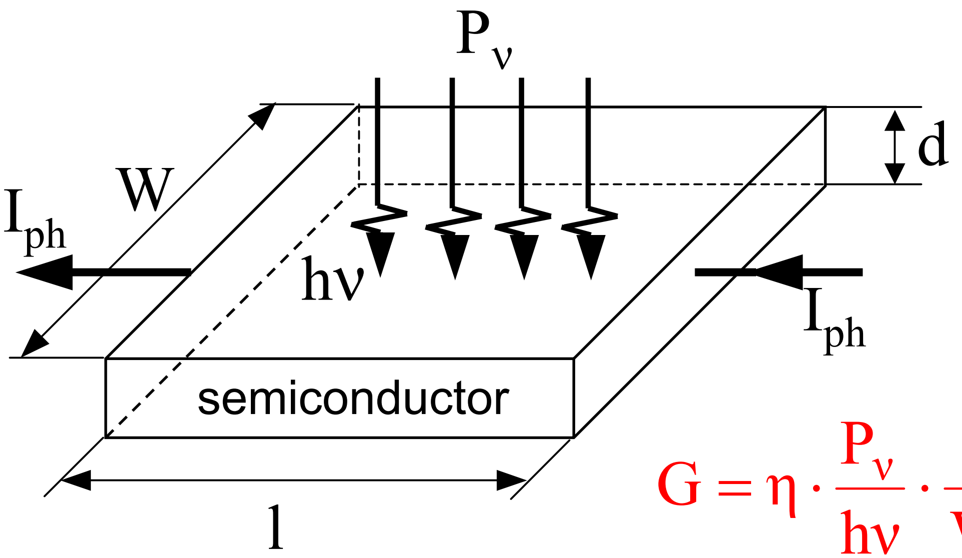
spontaneous emission

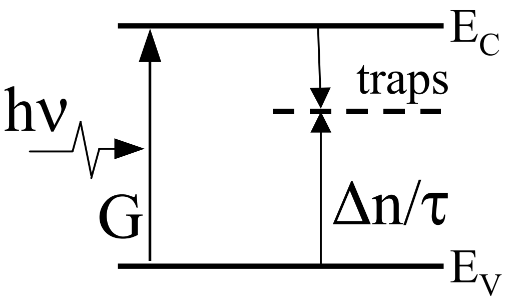
Auger

$$R = \frac{n}{\tau}, \quad \frac{1}{\tau(n)} = A + B \cdot n + C \cdot n^2$$

Internal quantum efficiency: $$\eta = \frac{{}^{1}\!/_{\tau_\nu}}{{}^{1}\!/_{\tau_\nu} + {}^{1}\!/_{\tau_d} + {}^{1}\!/_{\tau_A}}$$

Photoconductors





$$G = \eta \cdot \frac{P_\nu}{h\nu} \cdot \frac{W \cdot l}{W \cdot l \cdot d}$$

G – generation rate

η – quantum efficiency

P_ν – incident optical power density, W/cm²·sec

$W \cdot l = \text{Area}; \; W \cdot l \cdot d = \text{Volume}$

$n = n_0 + \Delta n$, $\Delta n << n_0$ $\Rightarrow G = \dfrac{\Delta n}{\tau}$, where τ is lifetime of carriers

For $\mu_e >> \mu_h$ ($\mu_{e,h}$ is mobility of electrons or holes)

$$I_{ph} = q \cdot \mu_e \cdot \Delta n \cdot E \cdot (W \cdot d) = q \cdot \eta \cdot \frac{P_\nu}{h\nu} \cdot W \cdot l \cdot \frac{\mu_e \cdot E \cdot \tau}{l} = q \cdot \eta \cdot \frac{P_\nu}{h\nu} \cdot W \cdot \mu_e \cdot E \cdot \tau$$

Photocurrent is proportional to incident power density, mobility, lifetime and applied field (voltage). Lifetime τ is usually more than 10^{-8} s.

Photoconductors

Temporal dependence of photoconductivity

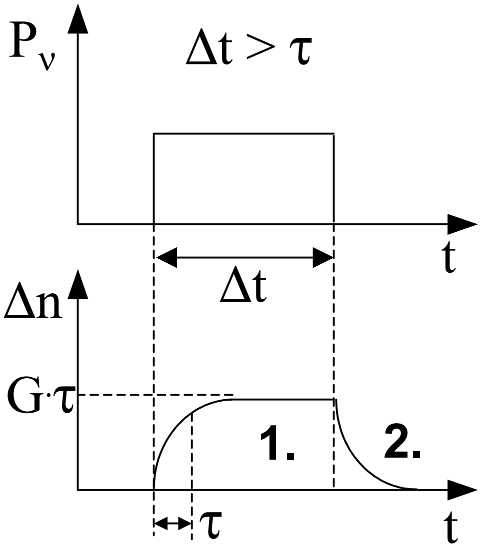
1. Rate equation for photocarriers concentration Δn is: $\frac{d\Delta n}{dt} = G - \frac{\Delta n}{\tau}, \quad \Delta n|_{t=0} = 0$

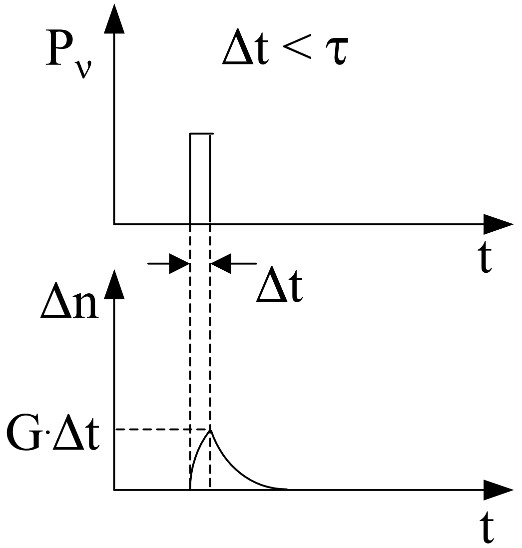
G - number of electron-hole pairs created by light in one cm³ per a second

$$\Delta n = G \cdot \tau \cdot \left(1 - e^{-t/\tau}\right); \qquad t \to \infty, \quad \Delta n \to \Delta n = G \cdot \tau$$

2. When $G=0$ rate equation reduces to: $\frac{d\Delta n}{dt} = -\frac{\Delta n}{\tau}, \quad \Delta n|_{t=0} = G \cdot \tau$

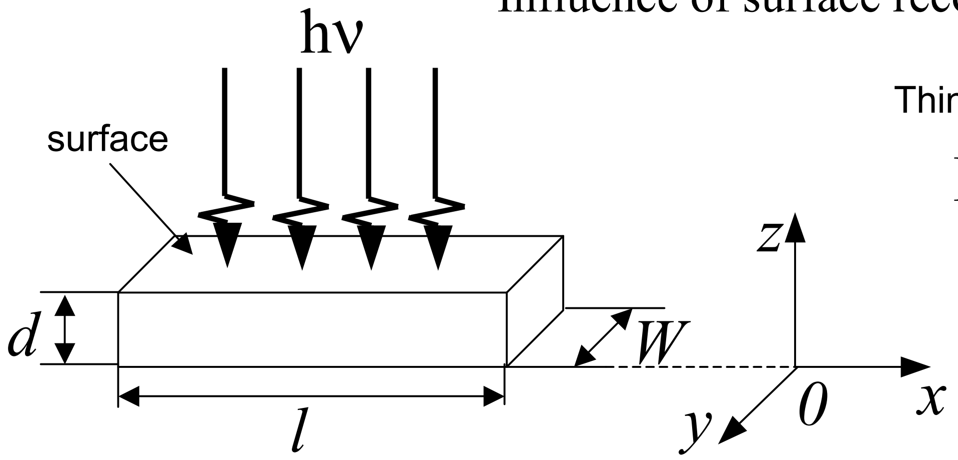
$$\Delta n = G \cdot \tau \cdot e^{-t/\tau}; \qquad t \to \infty, \quad \Delta n \to 0$$





Photoconductors

Influence of surface recombination



Thin semiconductor slab: $d << L_d\,,\;\; W, l > d$

$$L_d = \sqrt{D \cdot \tau}\;\text{- diffusion length}$$

$$\frac{1}{q} \cdot j_n \Big|_{z=0,d} = s \cdot \Delta n \Big|_{z=0,d}$$

G - number of carriers born by light in one cm^3 per a second

In steady state: $G \cdot d \cdot W \cdot l = \frac{\Delta n}{\tau} \cdot (d \cdot W \cdot l) + 2 \cdot s \cdot \Delta n \cdot (W \cdot l)$

$$G = \frac{\Delta n}{\tau} + \frac{2 \cdot s}{d} \cdot \Delta n \;\; \rightarrow \;\; G = \frac{\Delta n}{\tau_{eff}}; \qquad \frac{1}{\tau_{eff}} = \frac{1}{\tau} + \frac{2 \cdot s}{d}$$

$$s \approx 10^2 \div 10^6 \; {}^{cm}\!/_{s}$$

In thin semiconductors slab surface recombination decreases lifetime of photocarriers

Noises in photoconductors

1. Generation – Recombination noise (shot noise)

$$\left\langle i_{GR}{}^{2} \right\rangle \sim \frac{4 \cdot q \cdot I_{ph} \cdot B}{1 + (\omega \cdot \tau)^{2}}$$

is caused by fluctuation in the carrier concentration due to fluctuation in generation and recombination process. (B – device bandwidth)

2. Johnson noise

$$\left\langle i_{J}{}^{2} \right\rangle = \frac{4 \cdot k_B \cdot T \cdot B}{R}$$

results from random motion of carriers with average energy $k_B T$. (R – resistance)

3. Flicker or 1/f noise

$$\left\langle i_{f}{}^{2} \right\rangle \sim \frac{1}{f}$$

important at low frequencies f < 1kHz
results from surface defects and traps in bulk semiconductor

4. Noise caused by fluctuations in background radiation

Noises in photoconductors