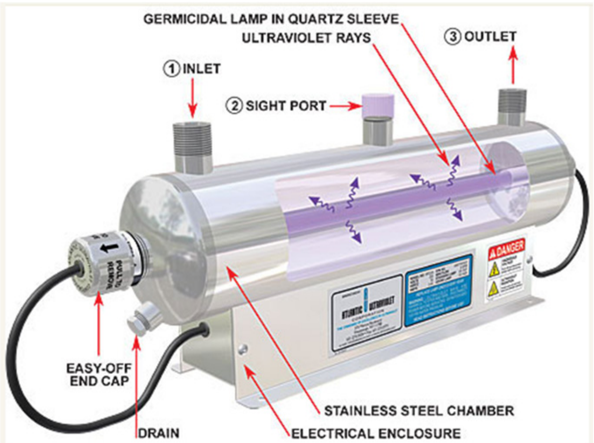
Lecture 9 – 16/04/2025

Light-emitting diodes
- Basic properties
- Notion of efficiency

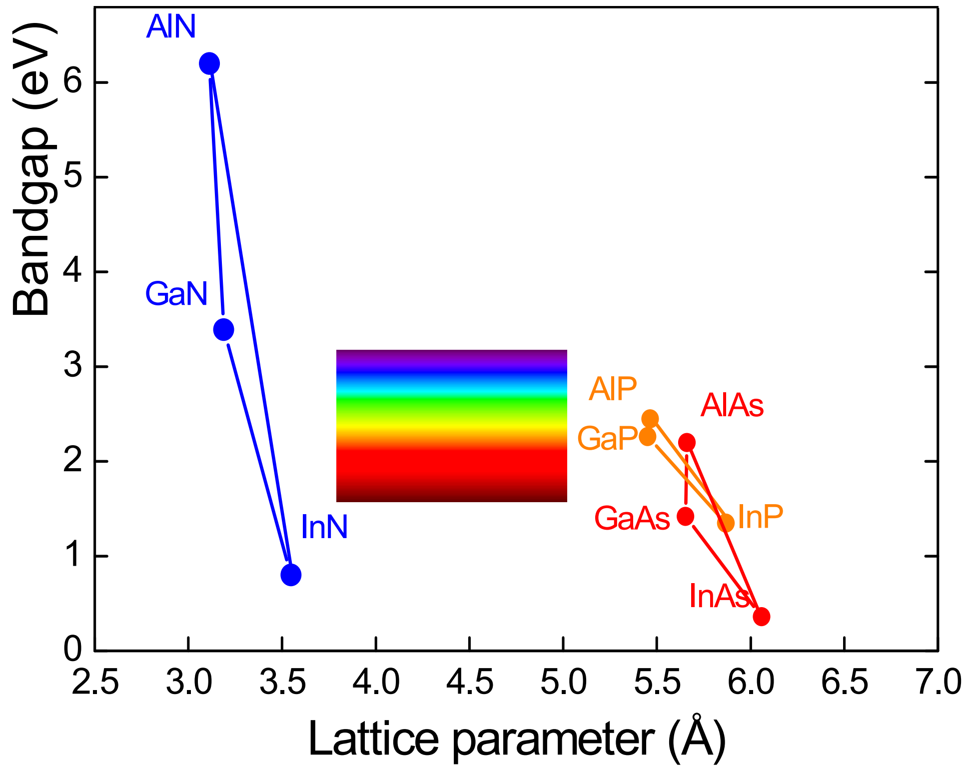
Chap. 13 in Rosencher-Vinter ≡
reference chapter until Lecture 14!

Main applications of light-emitting diodes

- Displays
- Lighting
- Communication
- Purification (UV)
- 3D sensing



Semiconductors for optoelectronics

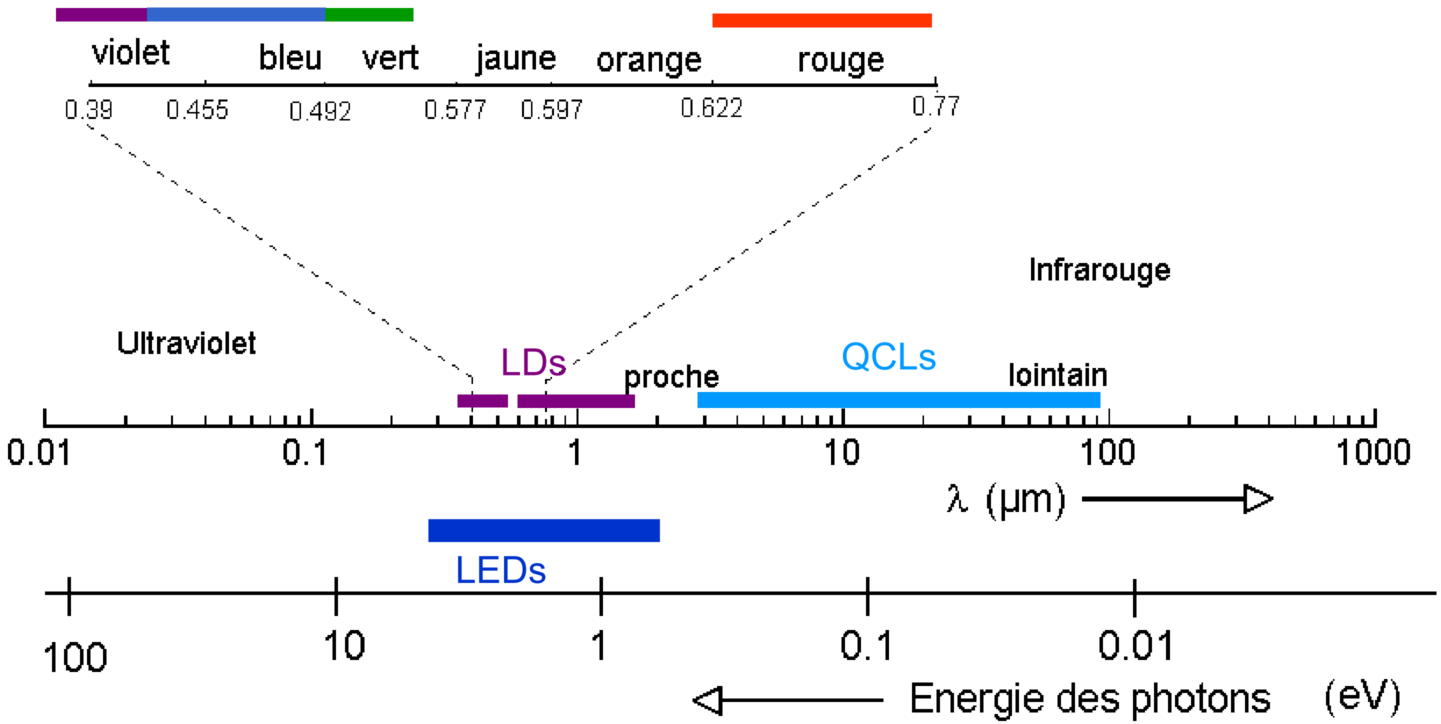


Arsenides: (Al,Ga,In)As

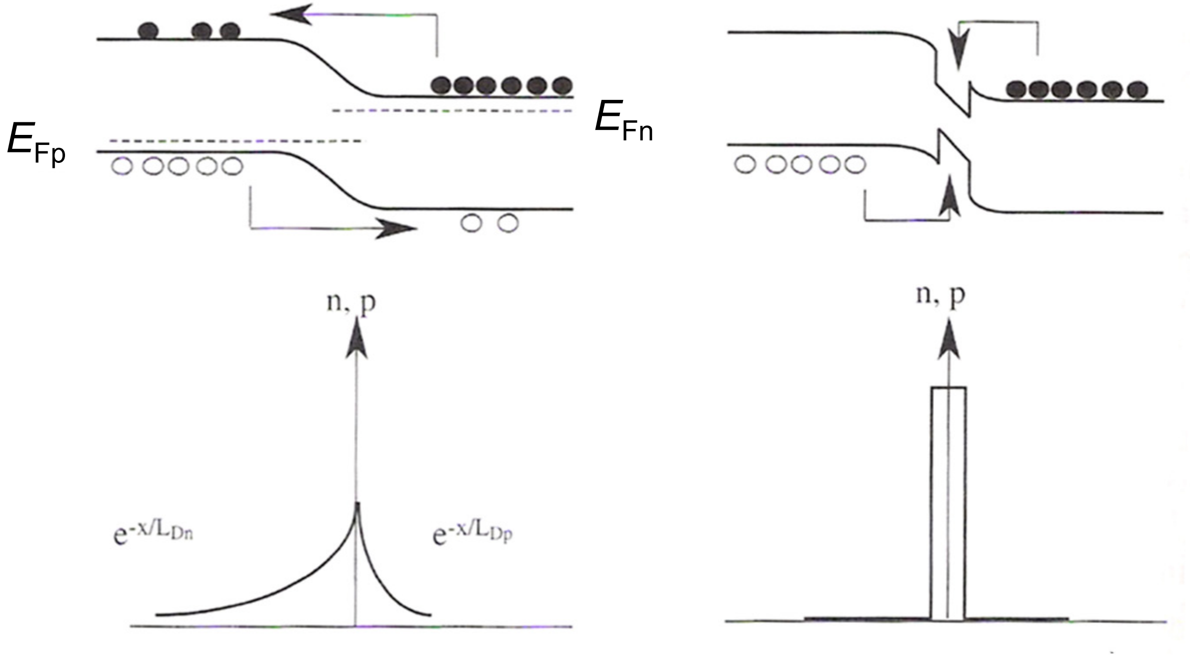
Phosphides: (Al,Ga,In)P

Nitrides: (Al,Ga,In)N

Spectral domain covered by commercial LEDs and LDs



LED structures

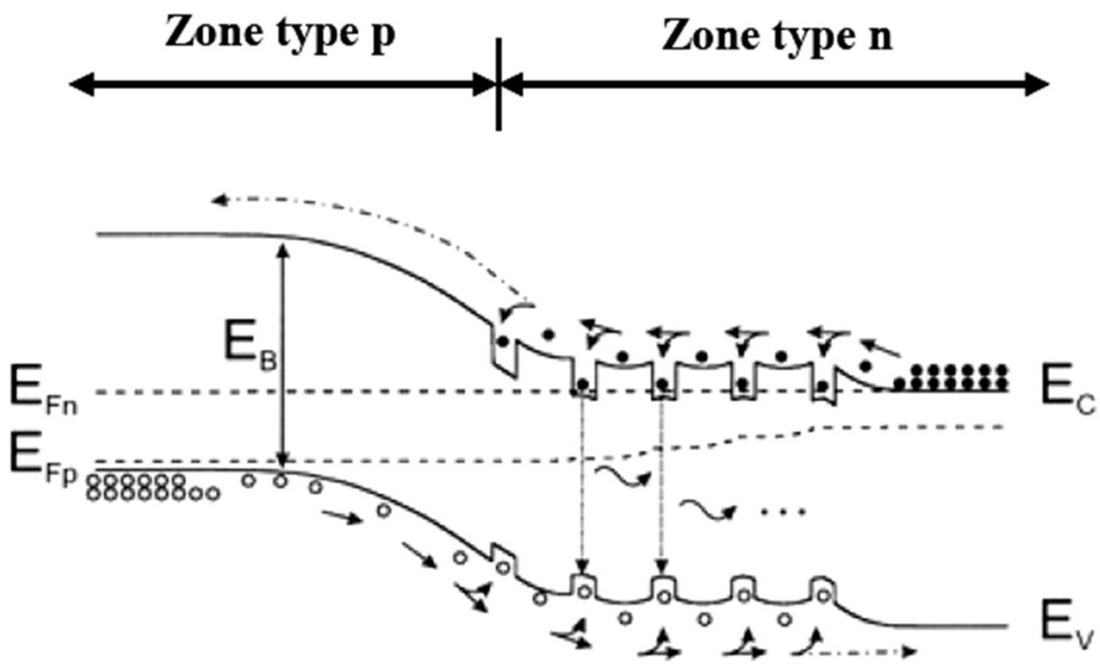


Homojunction **Heterojunction**

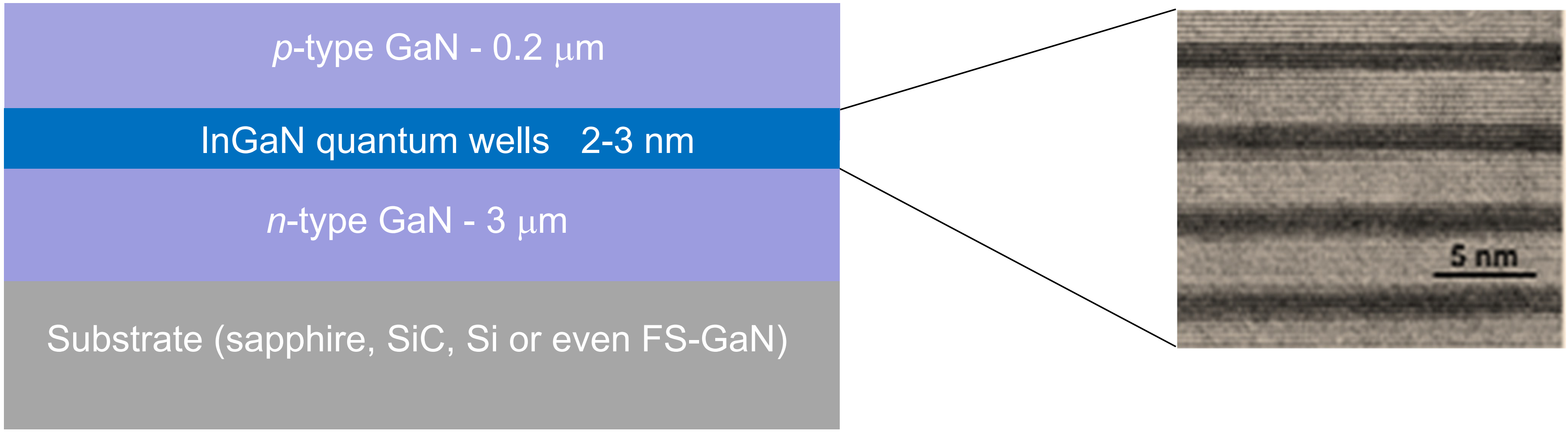
Heterojunction allows for an efficient spatial trapping of injected carriers ⇒ increased radiative efficiency, improved operating characteristics (*L*-*I* & *I*-*V* curves)

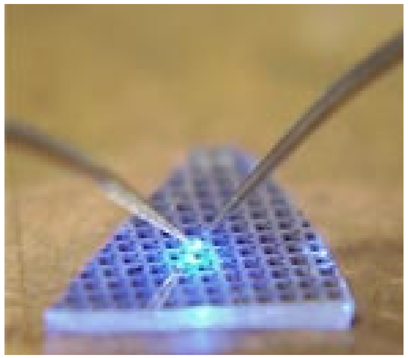
LED structures

Multiple quantum well LED



Blue LED structure: a basic picture





Substrate ⇒ epilayer material quality

***n*-type and *p*-type doped layers** ⇒ efficient injection

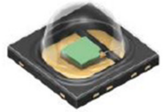
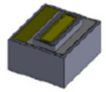
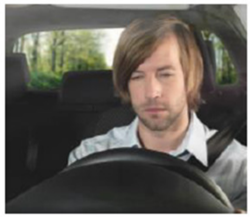
Active region ⇒ radiative efficiency

Key markets for III-N LEDs

- Automotive
  - Forward lighting
  - 3D sensing
- Consumer
  - Projection
  - Tablets/monitors/TV
- Industry
  - Video walls
  - White goods
  - 3D sensing
- General lighting
  - Indoor/outdoor lighting
  - Shop lighting

Sources: *OSRAM Opto Semiconductors*

Emerging LED market: toward 3D sensing

3D Sensing applications	Examples		Emitter technologies: LED	Edge emitter	VCSEL[2]
					
Mobile Devices			Not used for 3D Sensing	✓	✓ Deep-Dive
Industry			✓	✓	✓
Auto-motive[1]			✓	✓	✓

1) Different market that shows same emitter technology

2) Vertical-cavity surface-emitting laser

Sources: *OSRAM Opto Semiconductors*

LED chips: current trends

Evolution of chip sizes

Availability of chip technology at OS	Before 2000	From mid 2000s	Under development
	"Standard" LED	Mini LED	µLED
Chip size (µm)	>200	<200	100 to ~10 (2018) <10 (2020) <5 (2022) <2 for monolithic arrays (2025)

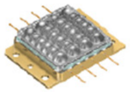
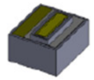
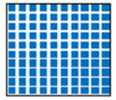
OS USP in µLED

- µLED chips in all colors
- Highest efficiency and reliability
- 6 inch production
- Access to transfer technology
- Proprietary packaging technology

Sources: *OSRAM Opto Semiconductors*

LED market

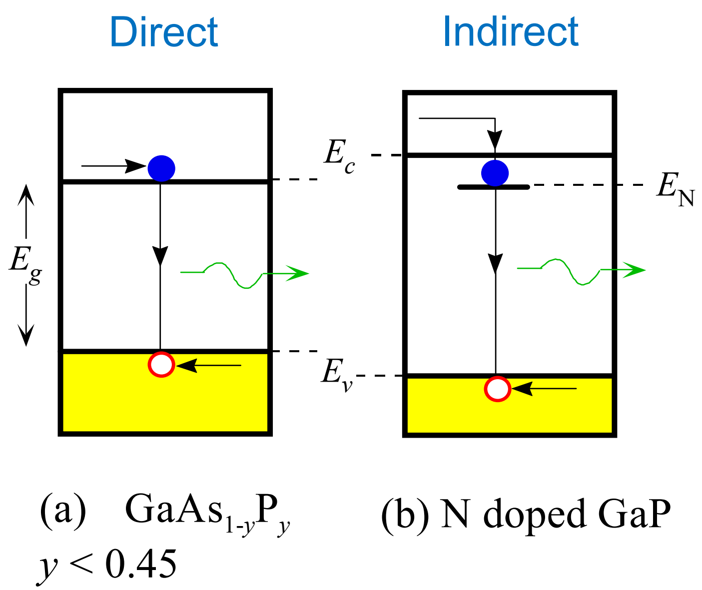
 Not used

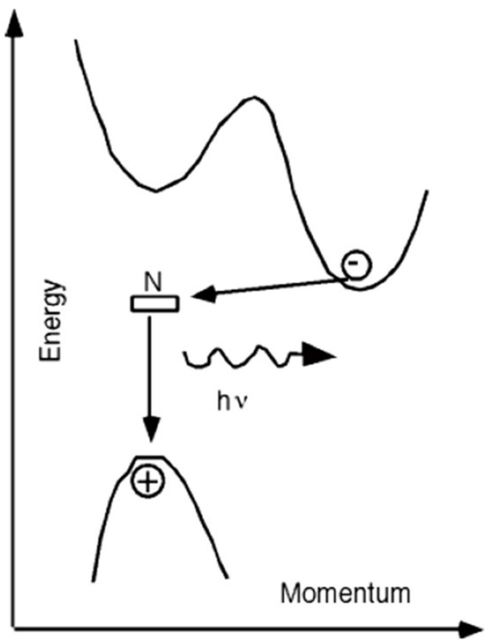
Projection applications		Emitter technologies: LED 	High power blue Laser 	RGB low power laser 	Pixelated µLED array 
Home Projection		✓			
Professional Projection		✓	✓		
Mobile Projection		✓		✓	
Augmented Reality		✓		✓	✓ Future scope

Sources: *OSRAM Opto Semiconductors*

LEDs: basic properties

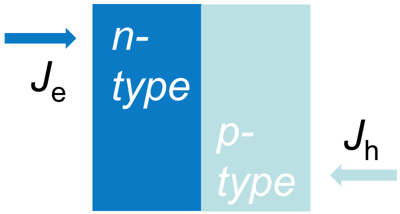
LEDs made of indirect bandgap semiconductors



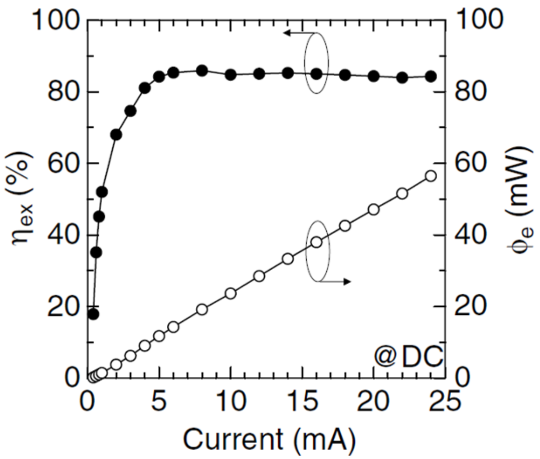


Indirect bandgap ⇒ luminescence through a localized defect lying within the bandgap

LEDs: basic properties



Cf. Lectures 7 & 14, fall semester + Chap. 7 Rosencher-Vinter



$$\frac{J_e}{qd} = \frac{J_h}{qd} = \frac{J}{qd} = \frac{n}{\tau_{tot}} = A_{nr}n + Bn^2 + C_{Aug}n^3$$

$d = V/S$ Thickness of the active region

$$\frac{1}{\tau_{nr}} = A_{nr} + C_{Aug}n^2$$

$$\frac{1}{\tau_r} = Bn$$ Stimulated emission term neglected

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

Out of equilibrium carrier density

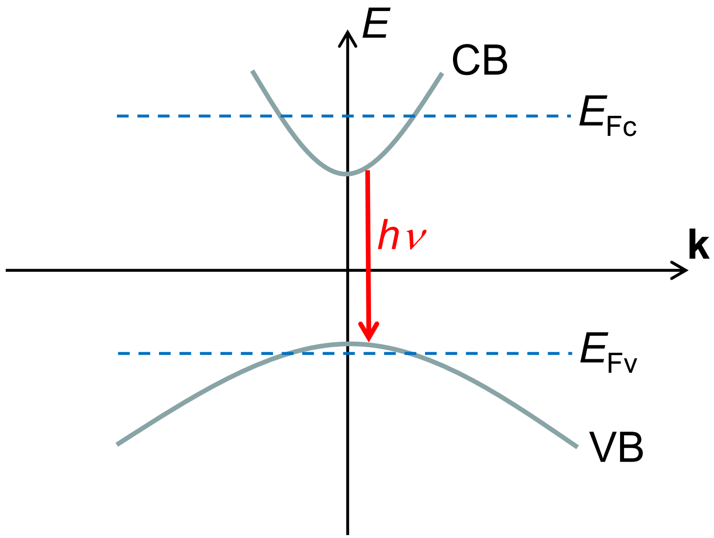
$$n = \frac{J\tau_{tot}}{qd}$$

$\Rightarrow$ Strong dependence on the thickness of the active region (homo- vs heterojunction (QWs, etc.))

Once n is known, possibility to derive the position of the quasi-Fermi levels E_{Fn} and E_{Fp}

Electrical injection

- Both the valence and the conduction bands get more and more filled upon increasing current injection
- The carrier populations are described by the quasi-Fermi levels E_{Fc} and E_{Fv}



$$f_c(E) = \frac{1}{\exp\left(\frac{E - E_{F_c}}{k_B T}\right) + 1}$$

$$f_v(E) = \frac{1}{\exp\left(\frac{E - E_{F_v}}{k_B T}\right) + 1}$$

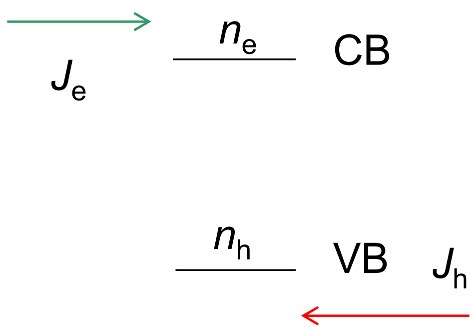
Note that here $f_v(E)$ describes the evolution of the electron population in the valence band!

Electrical injection

Determination of the quasi-Fermi level

$$n = \int_{E_c}^{\infty} \frac{1}{\exp\left(\frac{E - E_{F_c}}{k_B T}\right) + 1} \rho_c(E)\, dE$$

How many photons are emitted?



$J_e = J_h = J$ *electrical neutrality*

and $n_e = n_h = n$ (if the doping levels are not too high)

Steady-state $\Rightarrow$ recombination in the active region

The number of emitted photons is then given by

$R_{tot} \times$ Volume $= J/q \times S$ ← Contact size

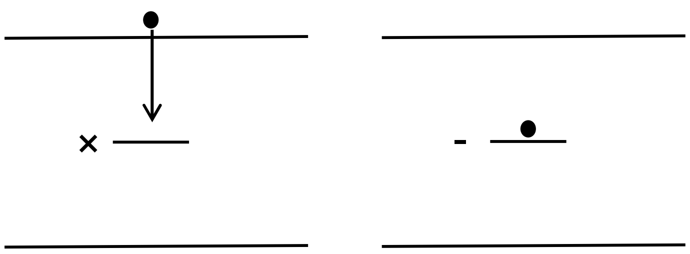
with R_{tot} the recombination rate (per unit volume)

Electrical injection

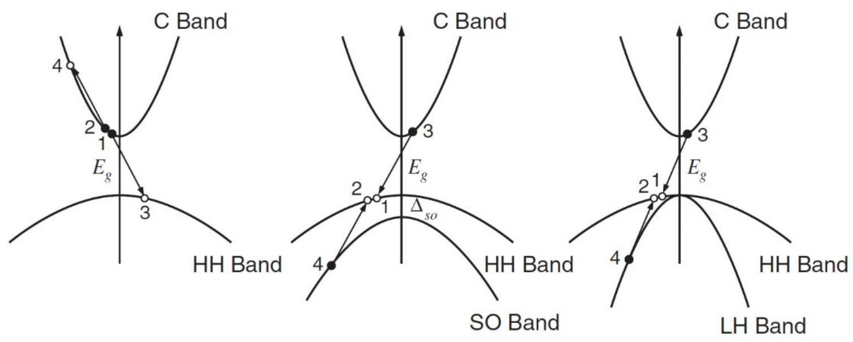
Different paths for electron-hole recombinations

Cf. Lecture 7, fall semester + Chaps. 5-7 Rosencher-Vinter

- Non-radiative $A_{nr}n$
- Spontaneous Bn^2 — B bimol. coeff. ~10^{-12}-10^{-10} cm^3s^{-1}
- Auger Cn^3



Shockley-Read-Hall recombinations



Auger recombinations

Quasi-Fermi levels in bulk semiconductors (reminder)

Example: quasi-Fermi levels in bulk GaAs

Non-degenerate case

$$E_{F_n} = E_C - k_B T \ln\left(\frac{N_C}{n}\right)$$

$$E_{F_p} = E_V + k_B T \ln\left(\frac{N_V}{p}\right)$$

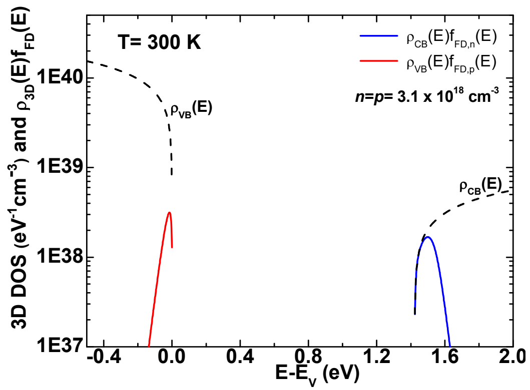
Degenerate case

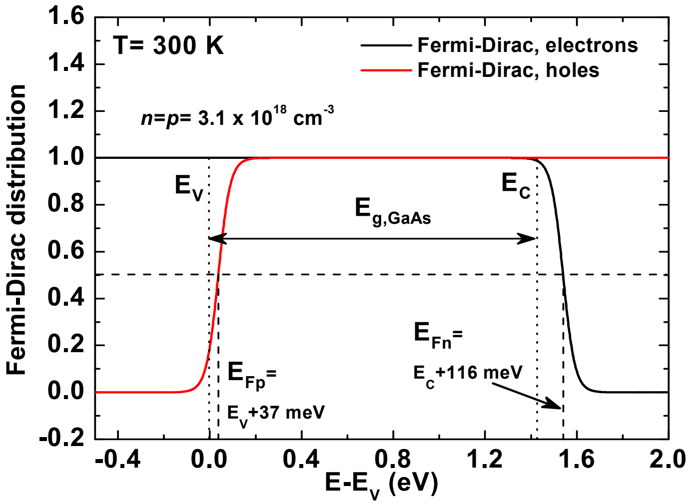
$$E_{F_n} = E_C + \frac{\hbar^2}{2m_C^*}\left(3\pi^2 n\right)^{2/3}$$

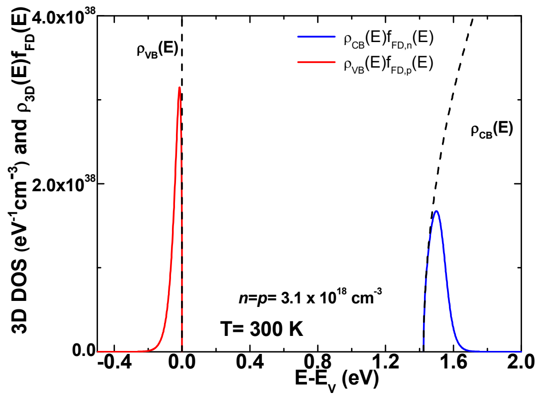
$$E_{F_p} = E_V - \frac{\hbar^2}{2m_V^*}\left(3\pi^2 p\right)^{2/3}$$

effective DOS

$$N_{C,V} = \frac{1}{4}\left(\frac{2m_{C,V}^* k_B T}{\pi\hbar^2}\right)^{3/2}$$







Spontaneous emission

In an intrinsic bulk semiconductor:

Cf. Lectures 12 & 14, fall semester
+ Chap. 7 Rosencher-Vinter

The spontaneous recombination rate (s^{-1}) between the CB and the VB is given for a state with a wavevector **k**

$$r_{sp}(\mathbf{k}) = A_{cv}\, f_c(E_c(\mathbf{k}))(1-f_v(E_v(\mathbf{k})))$$

with $A_{CV} = 1/\tau_R$ *the spontaneous recombination rate*

and the radiative lifetime is given by

$$\tau_R = \frac{\pi c^3 \hbar \varepsilon_0}{q^2 x_{vc}^2 n_{op} \omega_{vc}^3} = \frac{2\pi c^3 \hbar^2 \varepsilon_0 m_0}{q^2 n_{op} E_g E_P}$$

$\tau_R \uparrow$ *when* $E_g \downarrow$

with x_{vc} *the interband dipolar optical matrix element and* E_P *the Kane energy (~20-22 eV)*

$\Rightarrow$ *It is more challenging to achieve a laser based on a wide bandgap SC!*

Spontaneous emission

In an intrinsic bulk semiconductor: Cf. Lecture 14, fall semester + Chap. 7 Rosencher-Vinter

The spectral distribution of spontaneous recombination rate $R_{sp}(h\nu)$ due to a quasi-equilibrium distribution of carriers is then given by

Spin-related

$$R_{sp}(h\nu) = 2\sum_{\mathbf{k}} r_{sp}(\mathbf{k}) = 2\sum_{\mathbf{k}} \frac{1}{\tau_R(\mathbf{k})} f_c(\mathbf{k})\left(1 - f_v(\mathbf{k})\right)\delta\left(E_c - E_v = h\nu\right)$$

The summation is performed over all **k**-vectors verifying the energy conservation condition (hence the Dirac delta)

$$E_c(\mathbf{k}) - E_v(\mathbf{k}) = h\nu = E_g + \frac{\hbar^2 k^2}{2m_r}$$

Expression relying on the verticality of optical transitions in **k**-space

$$\frac{1}{m_r} = \frac{1}{m_C^*} + \frac{1}{m_V^*}$$

which leads to

$$R_{sp}(h\nu) = \int_0^\infty r_{sp}(E)\rho_j(E)\delta(E = h\nu)\mathrm{d}E = r_{sp}(h\nu)\rho_j(h\nu)$$

$$R_{sp}(h\nu) = \frac{1}{\tau_R}\rho_j(h\nu) f_c\left(E_c(h\nu)\right)\left(1 - f_v\left(E_v(h\nu)\right)\right)$$

Joint density of states (JDOS)

LEDs: basic properties

Spectral distribution of spontaneous recombination rate

$$R_{\mathrm{sp}}(h\nu)=\frac{1}{\tau_{\mathrm{r}}}\rho_{\mathrm{j}}(h\nu)f_{\mathrm{c}}(h\nu)\left(1-f_{\mathrm{v}}(h\nu)\right),$$

$$f_{\mathrm{c}}(h\nu)=\frac{1}{1+exp\left(\frac{E_{\mathrm{c}}(h\nu)-E_{\mathrm{F}_n}}{k_{\mathrm{B}}T}\right)}\cong exp\left(-\frac{E_{\mathrm{c}}(h\nu)-E_{\mathrm{F}_n}}{k_{\mathrm{B}}T}\right),$$

Usually valid for LEDs (non-degenerate case, i.e., Boltzmann approximation is valid)

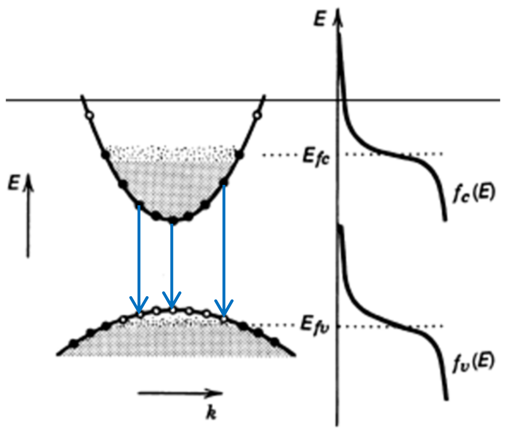
$$E_{\mathrm{c}}(h\nu)=E_{\mathrm{g}}+\frac{m_{\mathrm{r}}}{m_{\mathrm{c}}}\left(h\nu-E_{\mathrm{g}}\right),$$

$$f_{\mathrm{v}}(h\nu)=\frac{1}{1+exp\left(\frac{E_{\mathrm{v}}(h\nu)-E_{\mathrm{F}_p}}{k_{\mathrm{B}}T}\right)},$$

$$E_{\mathrm{v}}(h\nu)=-\frac{m_{\mathrm{r}}}{m_{\mathrm{v}}}\left(h\nu-E_{\mathrm{g}}\right),$$

$$\rho_{\mathrm{j}}(h\nu)=\frac{1}{2\pi^2}\left(\frac{2m_{\mathrm{r}}}{\hbar^2}\right)^{3/2}\left(h\nu-E_{\mathrm{g}}\right)^{1/2}.$$

Joint density of states (JDOS)

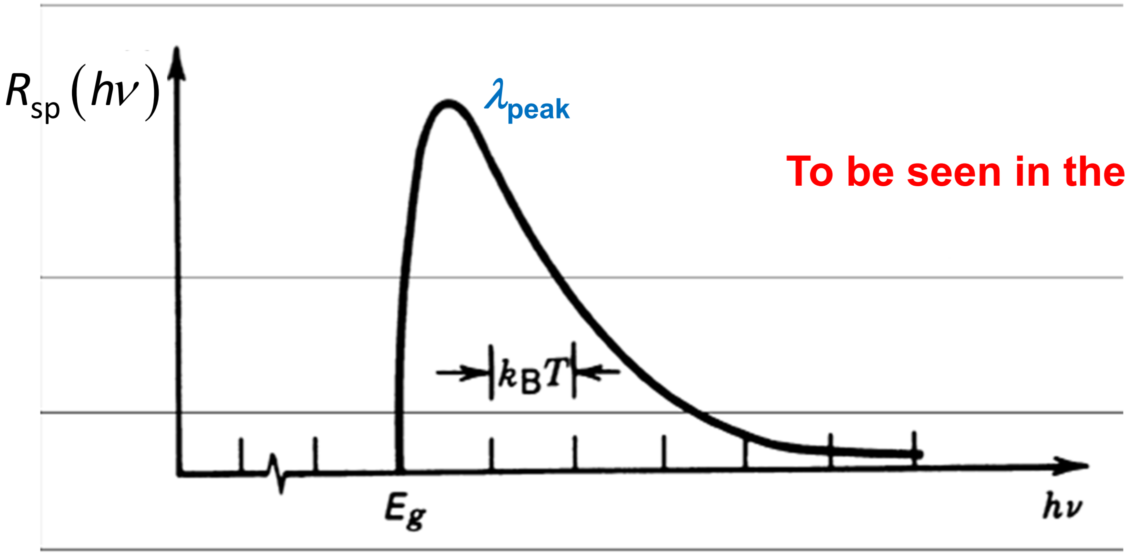


LEDs: basic properties

$$R_{sp}(h\nu) = K_{sp}(h\nu - E_g)^{1/2} \, exp\left(-\frac{h\nu - E_g}{k_B T}\right),$$

$$\text{with} \quad K_{sp} = \frac{(2m_r)^{3/2}}{\pi\hbar^2\tau_r} exp\left(\frac{\Delta E_F - E_g}{k_B T}\right) = \frac{(2m_r)^{3/2}}{\pi\hbar^2\tau_r} \underbrace{e^{\frac{eV_{app} - E_g}{k_B T}}}_{\propto J}.$$

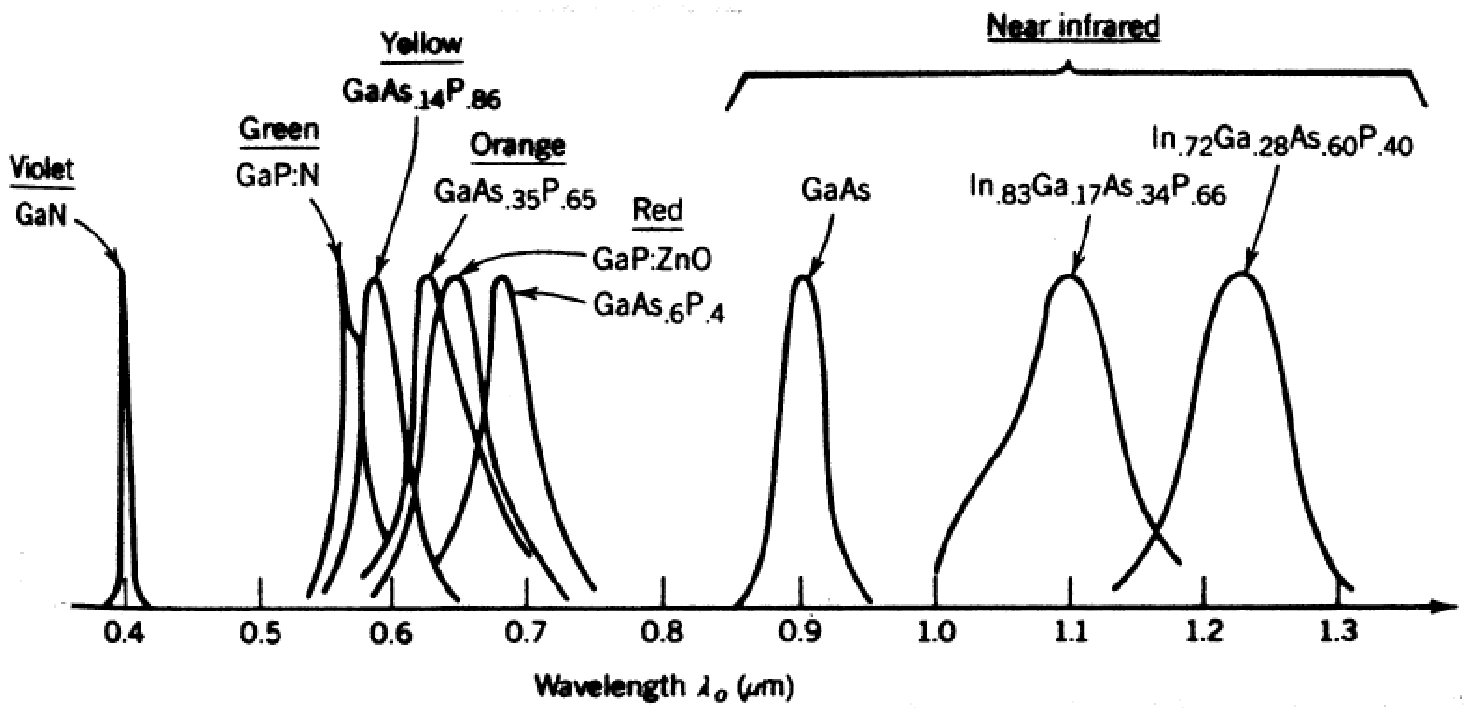
$\Delta E_F \rightarrow E_{F_C} - E_{F_V}$



To be seen in the series!

LEDs emission spectra

Spectral density emitted by LEDs



$$\Delta\lambda \propto \lambda_{\text{peak}}^{2} k_{\text{B}} T$$

LED efficiency

Internal quantum efficiency (IQE, η_i):

η_i = [generated photons]/[injected electrons]   with [] ≡ particle number

$$\eta_i = \frac{\tau_{tot}}{\tau_r} = \frac{\tau_{nr}}{\tau_{nr} + \tau_r} = \frac{Bn}{A_{nr} + Bn + Cn^2}$$

with τ_{nr} *non-radiative lifetime*

τ_r *radiative lifetime*

The internal quantum efficiency can be as high as 99% at 300 K for InGaN QWs!

The photon flux is $\Phi = \eta_{inj}\eta_i J/q$

Injection efficiency ≡ capture of carriers by the active region (QWs)

with J the electron current density

LED efficiency

External quantum efficiency (EQE, η): [emitted photons]/[electrons]

$$\eta = \eta_{inj}\eta_{i}\eta_{ext}$$ → extraction efficiency