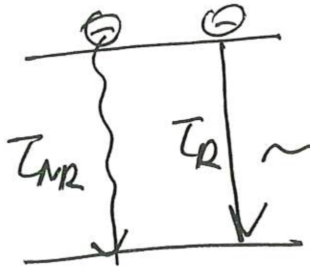
PH682 Semicond. Opt.

Lecture #4

Light emission in solids

radiative emission → luminescence → photoluminescence (PL)
→ electroluminescence (EL)



$\rightsquigarrow \hbar\omega$ $\quad \left(\frac{dN}{dt}\right)_{rad} = -\overset{\frac{1}{\tau_R}}{A} N$ ← upper level population

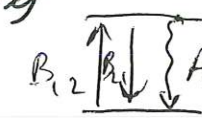
↑ Einstein coeff.

$$N(t) = N(0)\, e^{-At} = N(0)\, e^{-t/\tau_R}$$

↑ radiative lifetime

Since $A \sim B$ ⇒ transitions with large abs. coeff. α also have high emission probabilities and short radiative lifetimes

recall Einstein coeff.



degeneracy ↓ $\frac{g_2}{g_1}$

$B_{12} = B_{21} \frac{g_2}{g_1}$

$A_{21} = \frac{2\nu^3 h}{c^2} B_{21}$

$$I(h\nu) \sim |M|^2 g(h\nu) \cdot \text{level occupancy factors}$$

↑ luminescence intensity; ↑ matrix element; ↑ DOS; ↑ probabilities that the relevant upper level is occupied & lower level empty

Non-radiative relaxation → heat (phonon emission)
→ transfer energy to defects, etc.
faster time-scales

quantum eff.

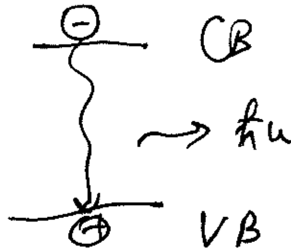
$$\eta_R = \frac{1}{1 + \frac{\tau_R}{\tau_{NR}}}$$

← if $\tau_R << \tau_{NR} \Rightarrow \eta_R \to 1$; efficient luminescence

if $\tau_R >> \tau_{NR}$ ↓ $\eta_R \to 0$ ↑ no emission

$$\left(\frac{dN}{dt}\right)_{total} = -\frac{N}{\tau_R} - \frac{N}{\tau_{NR}} = -N\left(\frac{1}{\tau_R} + \frac{1}{\tau_{NR}}\right)$$

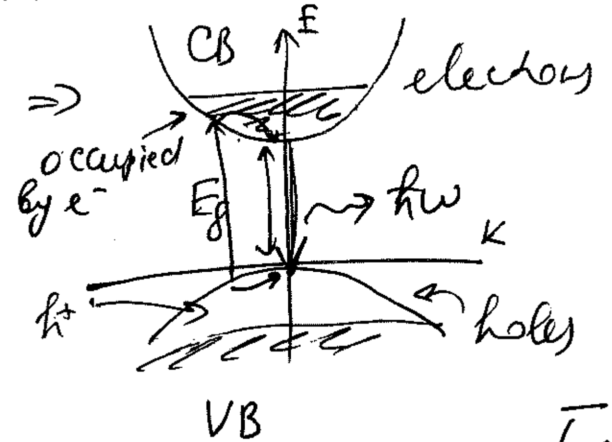
Interband luminescence



→ annihilation of $e^- - h^+$ pair ⇒ radiative $e^- - h^+$ recombination

(note: interband absorption ⇒ creation of $e^- - h^+$ pair)

Direct gap ⇒



Typically transitions are dipole-allowed ⇒ matrix element $|M|$ is large

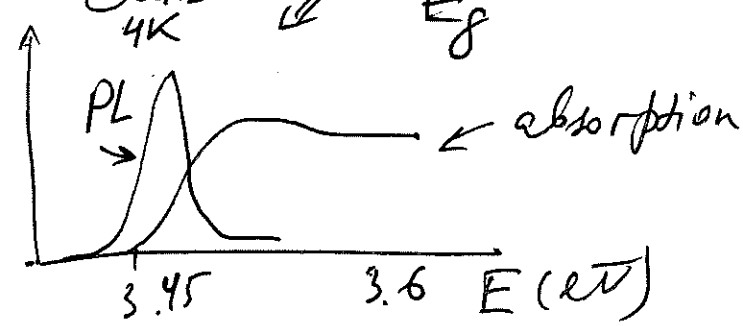
⇓

τ_R is short, 1–10 ns
lumines. eff. η_R high

After injection of electrons & holes (optical or electric)

⇓

e^- relax to the bottom of CB (within $k_B T$) ⇒ emission at energies close to E_g
h^+ — " — VB



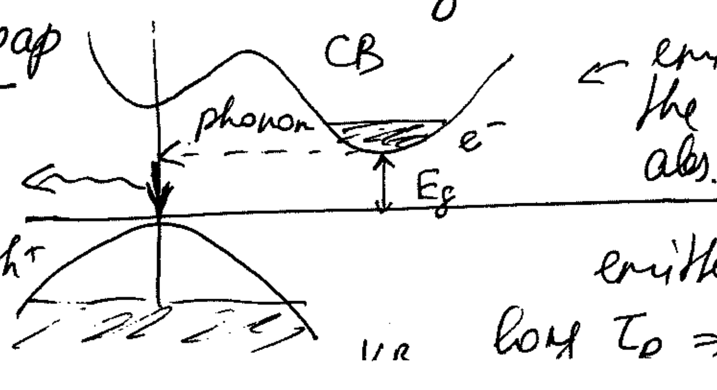
So, for an emitter

⇓

choose semicond. with
$E_g \simeq \hbar\omega$ ← desired emission freq.

For a photodetector – anything works if $\hbar\omega$ to be detected is $> E_g$

Indirect gap



↑
Si, Ge
↓
not good emitters!

← emission is the reverse of the abs. process ⇒ requires abs. or emission of a phonon when the photon is emitted ⇒ 2nd order process

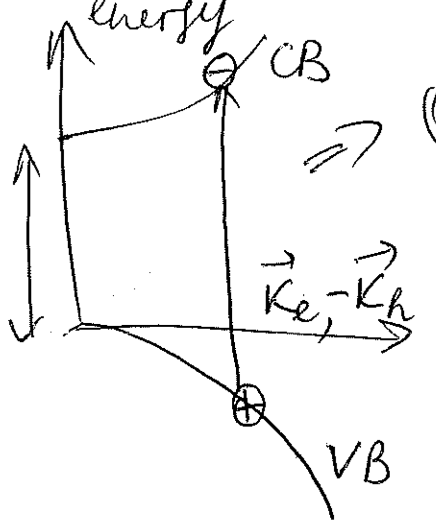
long τ_R ⇒ low η_R

PH 682
Semicond.
Optics

Excitons

(1)

Electron – hole pair excitation quantum $\Rightarrow$ "exciton"



$\Rightarrow$ (H)-like problem with a Coulomb interaction $\dfrac{-e^2}{4\pi\varepsilon_0 |\vec{r}_e - \vec{r}_h|}$

$\Downarrow$

For simple parabolic bands & a direct-gap semiconductor $\Rightarrow$ separate relative motion of e^- & h^+ and the motion of the center of mass $\Rightarrow$

$$E_{ex}(n_B, \vec{K}) = E_g - R_y^* \frac{1}{n_B^2} + \frac{\hbar^2 K^2}{2M},$$

$E_n^{H\text{-like}} = -\dfrac{E_I^{(H)} z^2}{n^2}$

$\dfrac{e^2}{2a_B^{(H)}}$

$R_y^* = 13.6\ \mathrm{eV} \cdot \dfrac{\mu}{m_0} \dfrac{1}{\varepsilon^2}$ $\leftarrow$ exciton Rydberg energy

$n_B = 1, 2, 3, \ldots$ $\leftarrow$ principal quantum number

$M = m_e + m_h$, $\vec{K} = \vec{k}_e + \vec{k}_h$

translational mass $\uparrow$ wave vector of the exciton

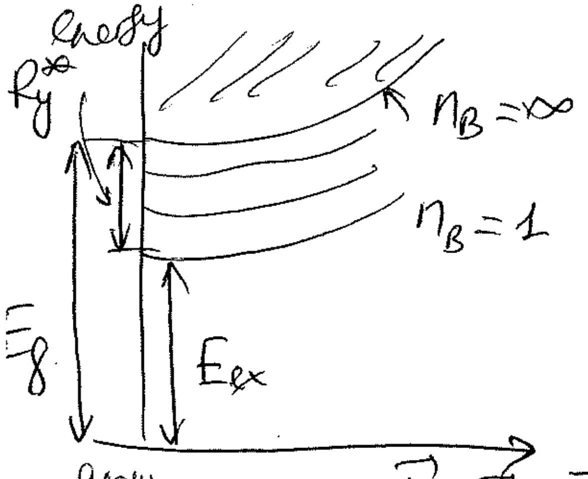
$$\mu = \frac{m_e m_h}{m_e + m_h}$$

reduced exciton mass

$$a_B^{ex} = a_B^{(H)} \, \varepsilon \, \frac{m_0}{\mu} \; ; \; r_n = n_B^2 \, a_B^{ex}$$

excitonic Bohr radius

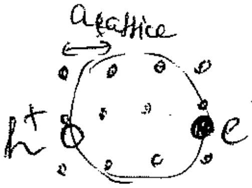
radius of $e^- - h^+$ orbit



Typical inorganic semiconductors

$1\,meV \leq Ry^{*} \leq 200\,meV \ll E_g$

$50\,nm \gtrsim a_B \gtrsim 1\,nm > a_{lattice}$



justifies the effective mass approximation

Wannier excitons

can be described in the framework of semicond. Bloch equations

exciton wave function

$$\varphi(\vec{K}, n_B, l, m) =$$

$$= \underbrace{\frac{1}{\sqrt{\Omega}}}_{\text{normalization}} \, \underbrace{e^{i\vec{K}\cdot\vec{R}}}_{\text{free propagation}} \, \varphi_e(\vec{r}_e)\, \varphi_h(\vec{r}_h)\, \underbrace{\varphi^{env}_{n_B,l,m}}_{\text{(H)-like function}} (\vec{r}_e - \vec{r}_h)$$

normalization

free propagation of a Wannier exciton through the periodic crystal (similar to the Bloch waves)

(H)-like function describing relative e^- & h^+ motion

$l < n_B, \quad |m| \leq l$

center of mass

$$\vec{R} = \frac{m_e \vec{r}_e + m_h \vec{r}_h}{M}$$

Typical values; $a_B^* = \frac{\hbar^2}{e^2} \frac{\varepsilon_r m_0}{\mu} \left(\frac{m_0}{\mu} \varepsilon_r^2 R_x \right)$ (9)

	E_g (eV)	Ry^* (meV)	a_B^{ex} (nm)
GaN	3.5	23	3.1
ZnSe	2.8	20	4.5
CdS	2.6	28	2.7
ZnTe	2.4	13	5.5
CdSe	1.8	15	5.4
CdTe	1.6	12	6.7
GaAs	1.5	4.2	13
InP	1.4	4.8	12
GaSb	0.8	2.0	23

Note: as $E_g \downarrow$, $Ry^* \downarrow$, $a_B^{ex} \uparrow$ => due to

$\varepsilon \uparrow$ & $\mu \downarrow$ as $E_g \downarrow$

$\left(a_B^{ex} \sim \frac{\varepsilon}{\mu}, \; Ry^* \sim \frac{\mu}{\varepsilon^2} \right)$

In "insulators", $a_B^{ex} \approx a_{lattice}$ => Wannier model not valid => Frenkel exciton
(including ord. semicond.)

In narrow-gap semicond. => Ry^* is small => excitons are hard to observe!

Excitons in external fields $\Rightarrow$ show! (5)

electric field $\mathcal{E}$ $\Rightarrow$ if $n_B = 1 \Rightarrow \mathcal{E}_{e-h} \overset{\downarrow}{=} \dfrac{2 R_y^*}{e\, a_B^{ex}} \Rightarrow$

if $\mathcal{E} > \mathcal{E}_{e-h} \Rightarrow$ field ionization

$\Rightarrow$ exciton breaks apart

magnetic field B $\Rightarrow$ if $R_y^* \gg \hbar \underbrace{\omega_c}_{\frac{eB}{\mu}} \Rightarrow$ weak field regime

for $n_B = 1$

$\Downarrow$

no net magnetic moment

$\Downarrow$

diamagnetic effects

energy shift $\Downarrow$ $n^2 a_B^{ex}$

$$\delta E = \frac{e^2}{12\mu} r_n^2 B^2$$

$R_y^* \ll \hbar\omega_c \Rightarrow$ strong field regime

$\Rightarrow$ Landau levels

excitonic effects cause a small shift in the energies of the optical transitions between the Landau levels

Wannier (free) excitons at high densities

$\Downarrow$

exciton-exciton distance $\approx$ exciton diameter $\Rightarrow$

$$N_{Mott} \approx \frac{1}{\frac{4}{3}\pi r_n^3}$$

Mott density

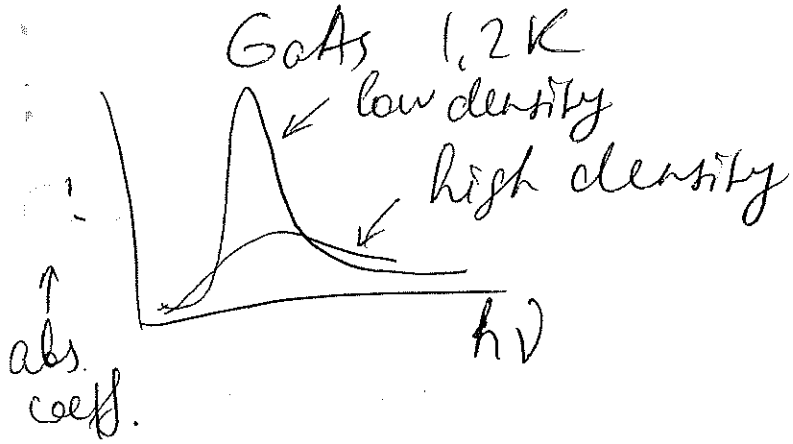
(for GaAs $n_B = 1 \Rightarrow$ $N_{Mott} \simeq 1.1 \cdot 10^{23}\, m^{-3}$)

easily achievable with a focused laser beam

$\Downarrow$

at $N > N_{Mott} \Rightarrow$

- exciton-exciton collisions $\to$ dissociation into an $e^- - h^+$ plasma $\Rightarrow$ reduction of absorption strength & broadening



- biexcitons ← "exciton molecules" (like $H + H \to H_2$)

  ↓

  CuCl, CdS, ZnSe, ZnO

  ↓

  $E_g = 3.4\,eV$, $R_y^* = 0.2\,eV$. At high density ⇒ new feature at $3.18\,eV$ ⇓ biexciton

  ↓

  So ground excitonic state is $3.2\,eV$ ⇐ ⇓ Binding energy of $0.02\,eV$

- $e^- h^+$ droplets ← Si, Ge

  ↖ Observed in the recomb. radiation ⇒ broad feature at lower energy than free exciton

- Bose-Einstein condensation

  ↗ Cu_2O, CuCl, coupled GaAs QW, CdTe QW in a microcavity ↓ exciton polaritons

  controversial for excitons

Other excitons ⇒ Frenkel excitons (tightly bound)

$R_y^* \sim 0.2 - 1\,eV$ ← organic semicond.