3.46 PHOTONIC MATERIALS AND DEVICES

Lecture 10: LEDs and Optical Amplifiers

Lecture

Notes

References: B. Saleh, M. Teich, Photonics, (John-Wiley), Chapters 15-16.

This lecture will review how electrons and holes recombine in semiconductors and generate photons. The study of light emission in materials is a key factor for the understanding of optoelectronic devices such as LEDs, Optical Amplifiers and Lasers.

Photon flux: $\phi_v = I\frac{1}{E_g} = \frac{P}{A}\frac{1}{E_g}$

I = optical power density
P = optical power
A = beam area

Non-equilibrium

R = non thermal generation rate (carrier injection rate)

G_0 = thermal generation rate

$$n = n_0 + \Delta n$$
$$p = p_0 + \Delta p$$
$$\Delta n = \Delta p$$
$$\Delta n \ll n_0,\ p_0$$

Injection carrier rate equation: $\frac{d(\Delta n)}{dt} = R - \frac{\Delta n}{\tau}$

τ = excess carrier recombination time (low injection level approximation)

$$G_0 = Bn_0p_0$$
$$G_0 + R = Bnp$$
$$R = \frac{\Delta n}{\tau}(e^-h^+ \text{pairs})/cm^3s$$
$$= B\Delta n(n_0 + p_0)$$
$$\tau \approx \frac{1}{B(n_0 + p_0)}$$

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Recombination: Non-equilibrium→equilibrium
Recombination rate = $B = B_r + B_{nr}$
B_r = radiative
B_{nr} = non-radiative
$B_{nr} \propto \sigma_{traps} \langle v \rangle$

Photon emission @ thermal equilibrium

GaAs $n_i = 1.8 \times 10^6 \text{cm}^{-3}$
$B_r = 10^{-10} \text{cm}^3/\text{s}$

$$G_0 = B_r n_i^2 = 324 \frac{\text{Photons}}{\text{cm}^3\text{s}}$$

thickness of layer: t = 2 μm = 2 x 10^{-4} cm
($\alpha \sim 10^4 \text{ cm}^{-1}$)

$$\phi_v = \left(B_r n_i^2\right) t = 6.48 \times 10^{-2} \text{cm}^{-2}\text{s}^{-1}$$

$$E_g = 1.42 \text{ eV}$$
$$= 2.27 \times 10^{-19} \text{J}$$

$$I = \phi_v E_g = 1.5 \times 10^{-20} \text{W/cm}^2$$

$\Rightarrow$ very low power

Internal Quantum Efficiency

Recombination = <u>release of energy</u>
radiating $\rightarrow h\upsilon$
non-radiating $\rightarrow h\nu_{phonon}$, Auger e^-

$$\eta_i = \frac{B_r}{B} = \frac{B_r}{B_r + B_{nr}}$$

$\eta_i = \frac{\tau}{\tau_r} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}}$: fraction of non-equilibrium carriers that recombine radiatively

R·V = injected (pairs)/s
↳ volume of active material

$$\phi = \text{ photon flux } = \frac{\eta_i RV}{A}$$
$$= \frac{\Delta n}{\tau_r} t$$

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Interband recombination
GaAs: η_i = 0.5
Si: η_i = 10^{-5}

$$\text{GaAs}: \tau \simeq 50\text{ ns}, \eta_i = 0.5, \Delta n = 10^{17}\text{ cm}^{-3}$$

$$R = \Delta n/\tau = 10^{24}\text{ photons/cm}^3/\text{s}$$

$$t = 2\ \mu\text{m}$$

$$\phi_v = Rt = 2\times10^{20}\text{ cm}^{-2}\text{s}^{-1}$$

$$I = \phi_v E_g = 46\text{ W/cm}^2$$

LED: $200\ \mu\text{m}\times100\ \mu\text{m}$ area
emitted power = 9 mW

Spontaneous emission

Rate = $r_{sp}(\nu) = \dfrac{1}{\tau_r}\rho(\nu)f_e(\nu)$

$$\rho(\nu) = \frac{(2m_r)^{3/2}}{\pi\hbar^2}(h\nu - E_g)^{1/2}$$

optical joint density of states

$$\frac{1}{m_r} = \frac{1}{m_v} + \frac{1}{m_c}\quad\text{(reduced mass)}$$

Emission condition

$$f_e(\nu) = f_c(E_2)\left[1 - f_v(E_1)\right]$$

prob CB state @ E_1 empty

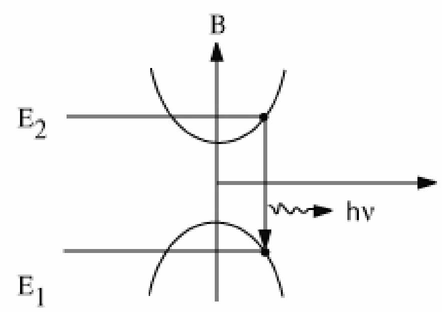
prob VB state @ E_2 filled

$$E_1 = E_2 - h\nu$$

$$E_2 = E_c + \frac{m_r}{m_c}(h\nu - E_g)$$

$$\phi = \frac{V}{A}\int_0^\infty r_{SP}(\nu)d\nu$$

$$= \frac{V(m_r)^{3/2}}{A\sqrt{2}\pi^{3/2}\hbar^3\tau_r}(k_B T)^{3/2}\exp\left[\frac{E_{FC} - E_{FV} - E_g}{k_B T}\right]$$



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(1) low injection ($\Delta n < n_0,\ p_0$)

$$R \uparrow \rightarrow \Delta n \uparrow \rightarrow (E_{FC} - E_{FV}) \uparrow \rightarrow f_e(\nu) \uparrow$$

(2) high injection ($\Delta n > n_0,\ p_0$)

$$(E_{FC} - E_{FV}) = E_g + (3\pi^2)^{2/3} \frac{\hbar^2}{2m_r} (\Delta n)^{2/3}$$

Spectral density of emission rate

$$r_{sp} = D(h\nu - E_g)^{1/2} \exp\left[\frac{-(h\nu - E_g)}{K_B T}\right]$$

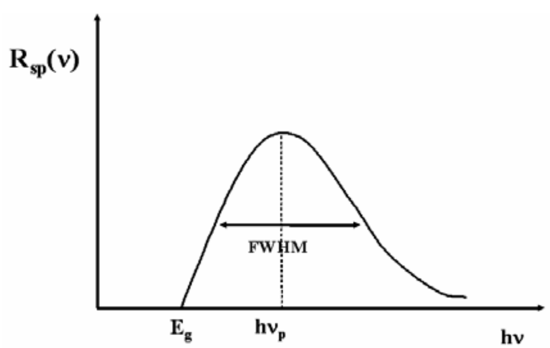
weak injection

$$D = \frac{(2m_r)^{3/2}}{\pi \hbar^2 \tau_r} \exp\left[\frac{(E_{FC} - E_{FV} - E_g)}{k_B T}\right]$$

same shape as thermal equilibrium:

$$r_{sp} = D_0 (h\nu - E_g)^{1/2} \exp\left[\frac{-(h\nu - E_g)}{K_B T}\right]$$

Where $\dfrac{D}{D_0} \sim \exp\left[\dfrac{(E_{FC} - E_{FV})}{k_B T}\right]$



ν_P = Peak frequency

$$h\nu_P = E_g + \frac{1}{2} k_B T$$

Notes

λ_g : bandgap wavelength

E_g : bandgap energy

$$\lambda_g = \frac{1.24\ \text{eV} \cdot \mu\text{m}}{E_g}$$

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FWHM

$$\Delta\nu = 1.8 k_B T / h \text{ Hz } (k_B T \text{ in eV units})$$

$$\Delta\lambda = 1.45 \lambda_p^2 k_B T \ \mu m$$

$$\simeq 350 \text{Å} \ @ \ \lambda_p = 1 \ \mu m$$

LED Devices

Internal photon flux

$$R = \frac{I/e}{V} = \text{ injection rate}$$

I = current
e = charge/e^-
V = active volume

@ high injection levels

$$\Delta n > n_0, p_0$$

$$\Delta n = \frac{\left(I/e\right)\tau}{V}$$

Internal quantum efficiency

$$\eta_i \equiv \frac{\text{photon flux}}{\text{electron flux}}$$

$$\phi = \eta_i \frac{I/A}{e}$$

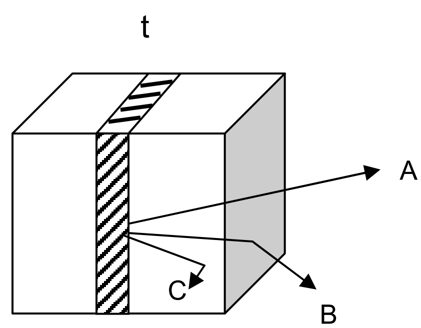
External quantum efficiency

$$\eta_{ext} = \frac{\text{external photon flux}}{\text{electron flux}}$$

$$\phi_{out} = \eta_{ext} \frac{I/A}{e}$$

Notes

$k_B T(300K) = 0.025$ eV



Surface emission

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1. Absorption $(h\nu \simeq E_g)$

$$\eta_1 = \exp(-\alpha t)$$

2. Reflection @ interface

$$\eta_2 = 1 - \frac{(n-1)^2}{(n+1)^2} = \frac{4n}{(n+1)^2}$$

= 0.68 for GaAs (n=3.6)

3. Total reflection

$$\eta_3 = 1 - \cos\theta_c \simeq \frac{1}{2n^2}$$

= 4% of GaAs

$$\eta_{ext} = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_i$$

output power $= P_0 = h\nu\phi_0$

$$P_{out} = \eta_{ext} \frac{h\nu}{e} I$$

Power conversion wall plug efficiency

$$\eta_W \equiv \frac{\text{emitted optical power}}{\text{input electrical power}}$$

$$= \frac{P_{out}}{IV} = \eta_{ext} \frac{h\nu}{e} \frac{1}{V}$$

V → voltage drop across device

Responsivity

$$R \equiv \frac{P_0}{I} = V\eta_W = \eta_{ext} \frac{h\nu}{e}$$

$$R = \eta_{ext} \frac{1.24}{\lambda_0(\mu m)} \frac{W}{A}$$

Typical:

η_{ext} = 1.5% ⇒ R = 10-50 μW/mA

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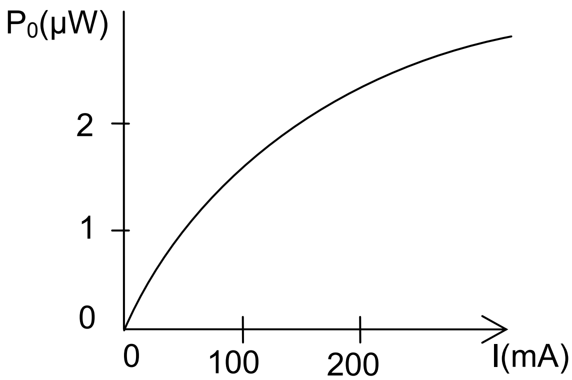
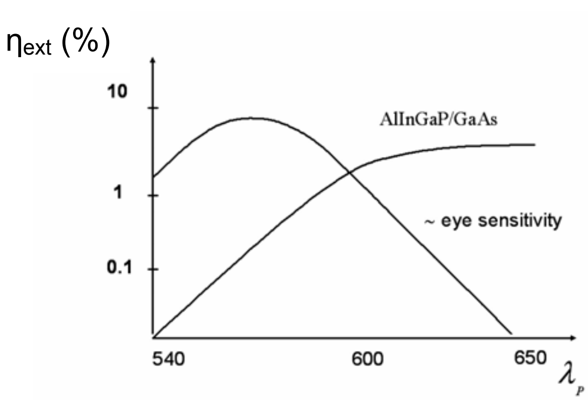
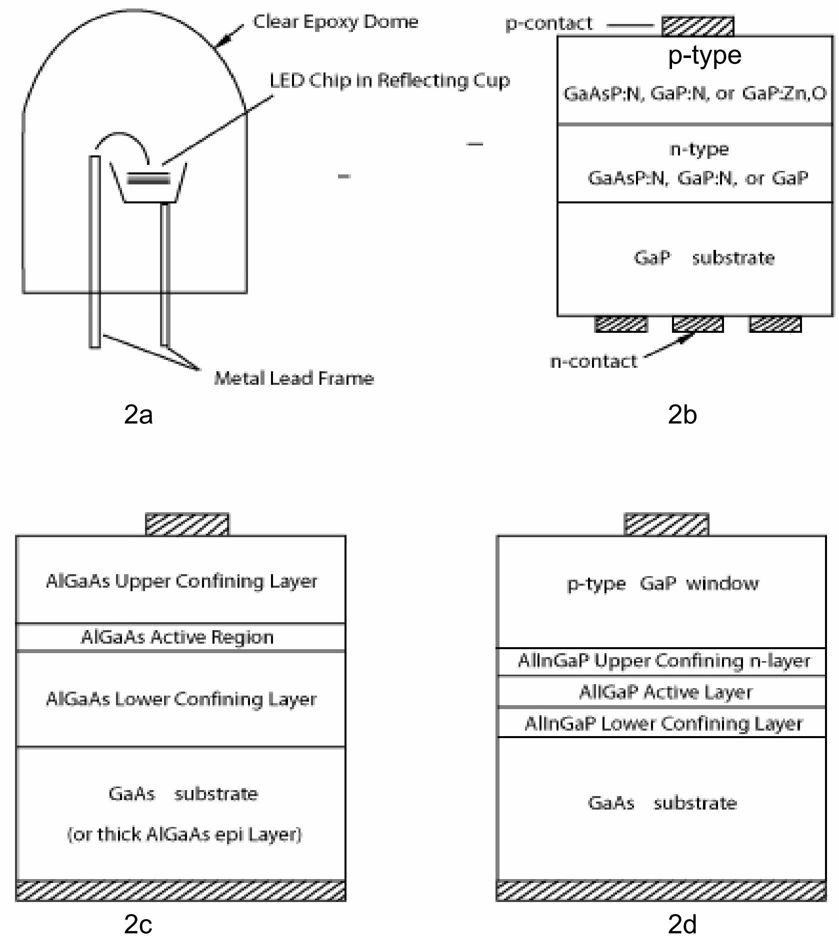


Luminous performance (displays)



Notes

$$\frac{\text{lumens}}{\text{IV}} = \frac{P_0 \cdot \text{eye sensitivity}}{\text{IV}}$$



2. Typical LED device and chip configurations. (a) Cross-section of a LED lamp. The LED chip, typically 250 x 250 x 250 micrometers, is mounted in a reflecting cup formed in lead frame. Clear epoxy acts as a lens, as well as performing other functions. (b) A conventional homojunction LED chip can be made with GaAsP:N/GaP structures to emit at red and yellow wavelengths, and with GaP:N/GaP structures to emit at green wavelengths. (c) In a red-emitting AlGaAs double-heterostructure chip, the entire structure is grown by LPE and can be either n-type or p-type on top. (d) An AlInGaP double-heterostructure with a GaP window layer for red, yellow, or green emitters. The Al concentration in the p-type active region is adjusted to give the desired color.