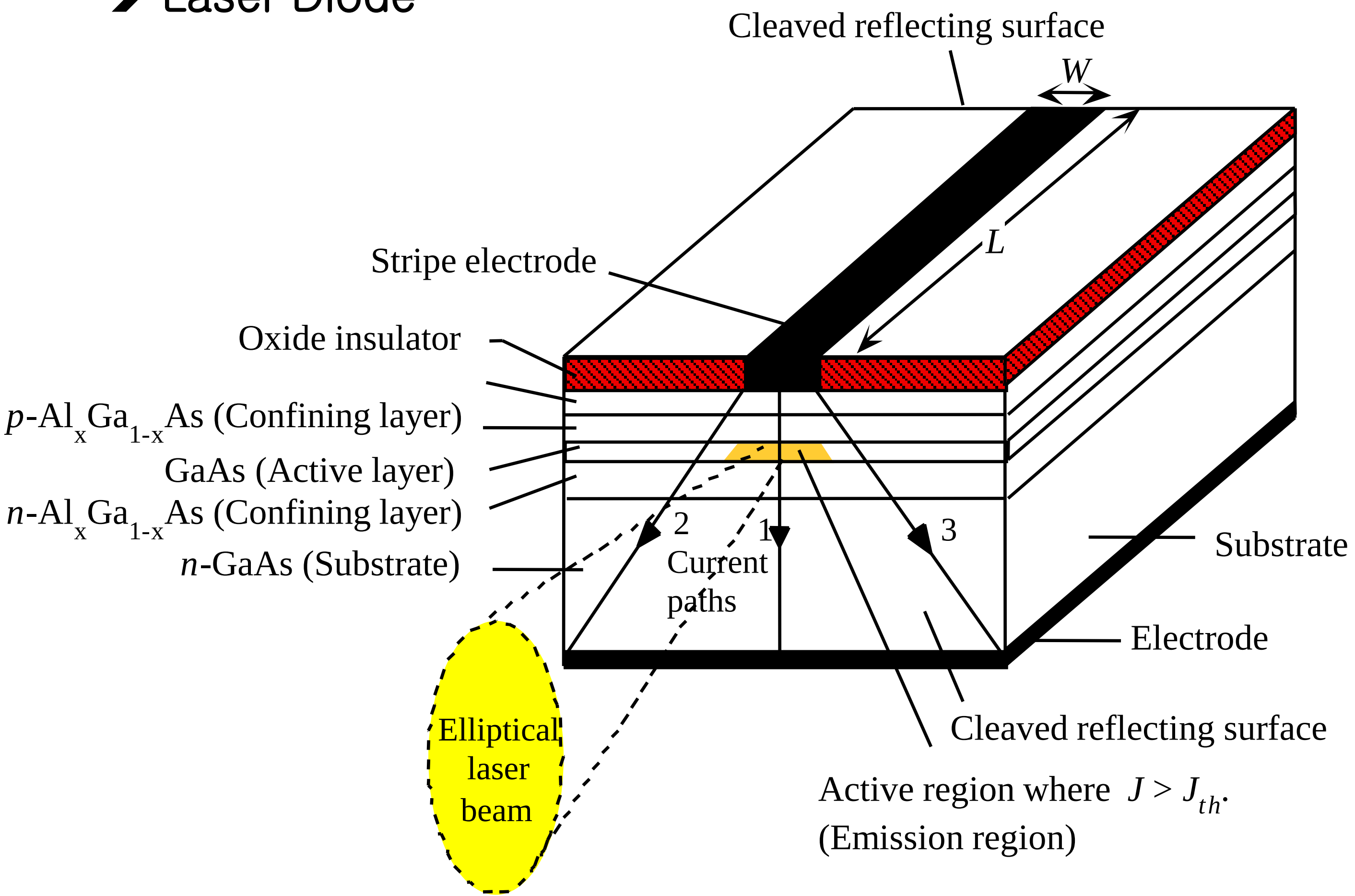
Lect. 24: Semiconductor Lasers

Semiconductor Laser: PN Junction + Mirrors (Cleaved Facets)

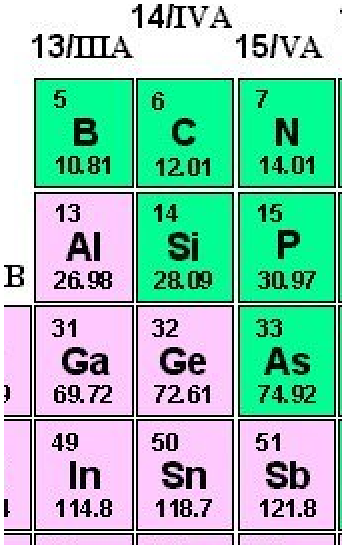
➔ Laser Diode



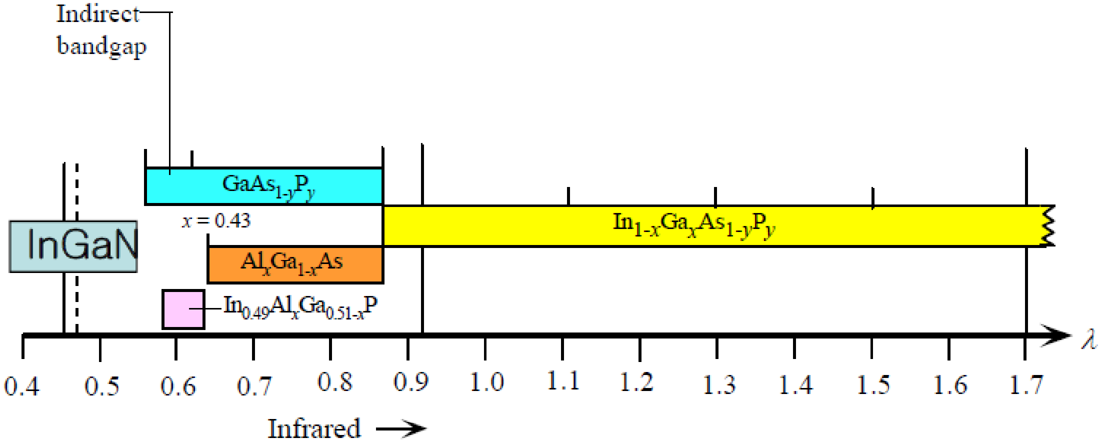
Lect. 24: Semiconductor Lasers

- Semiconductors lasers are small, cheap and very efficient
- Lasing wavelength:

Bandgap of direct semiconductor materials (III-V compound semiconductors)

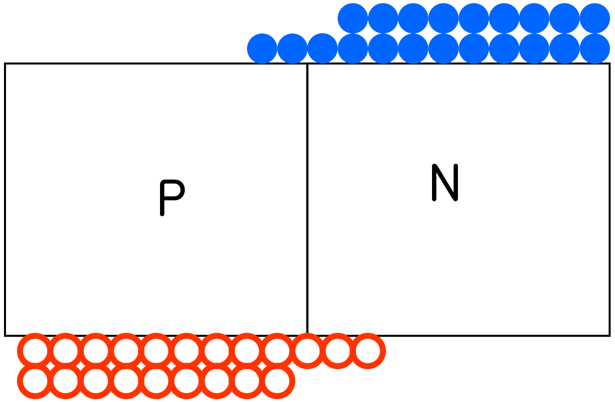


13/IIIA	14/IVA	15/VA
5 B 10.81	6 C 12.01	7 N 14.01
13 Al 26.98	14 Si 28.09	15 P 30.97
31 Ga 69.72	32 Ge 72.61	33 As 74.92
49 In 114.8	50 Sn 118.7	51 Sb 121.8

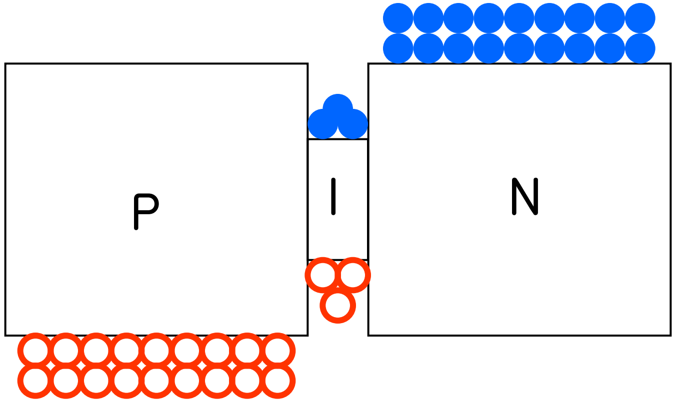


Lect. 24: Semiconductor Lasers

Efficient carrier confinement: PIN structure with large E_g for P, N regions



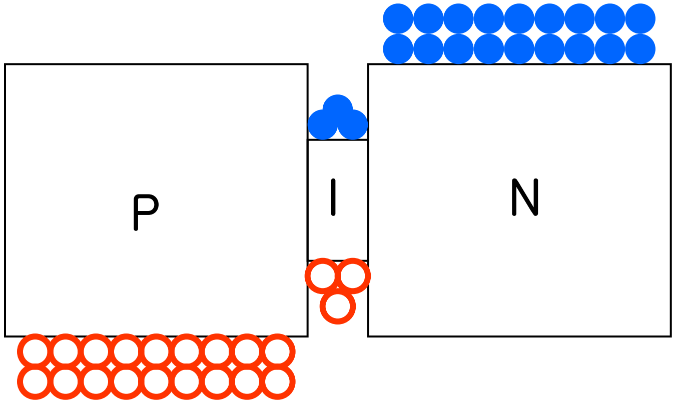
Injected carriers are spread-out
=> smaller density



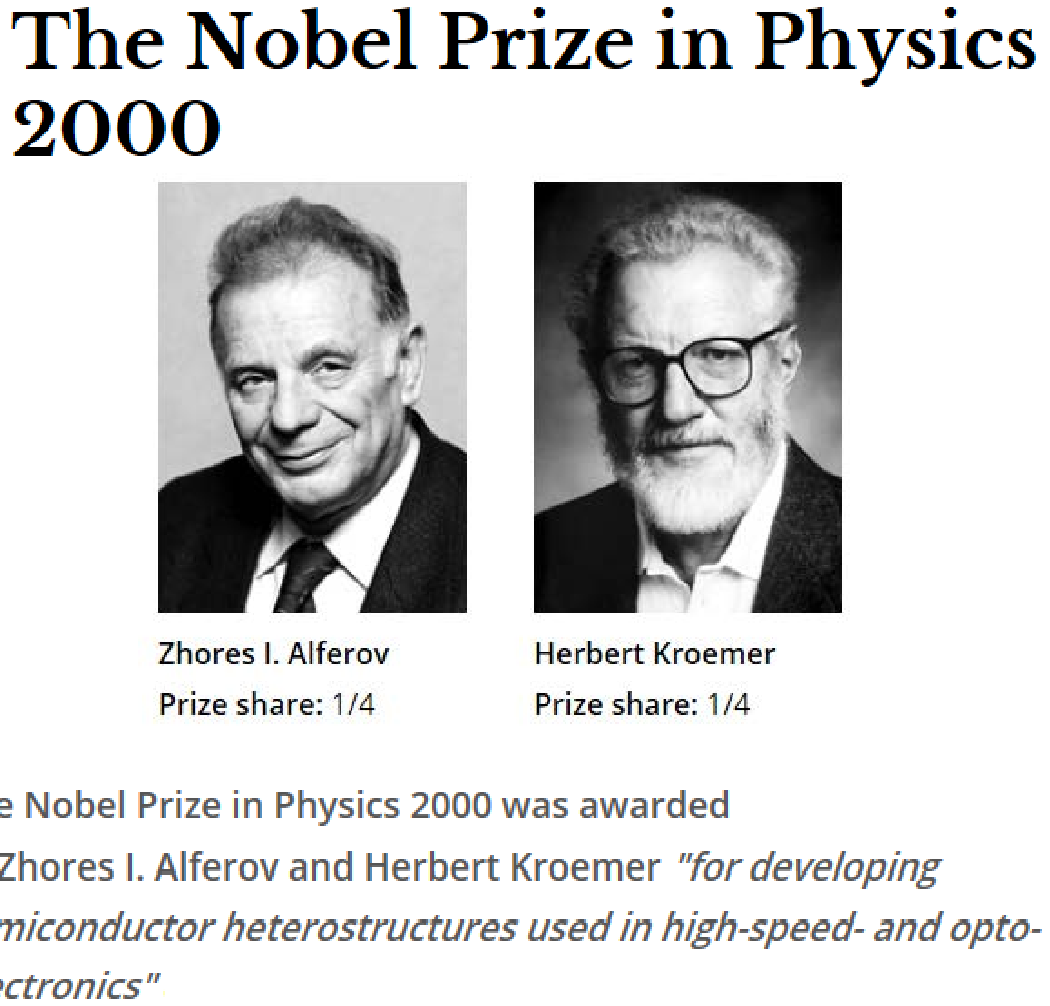
Double heterojunction: Confinement of
Injected carriers
=> larger density

For population inversion, $\frac{N_2 \cdot P_1}{N_1 \cdot P_2} > 1$

Lect. 24: Semiconductor Lasers



Double heterojunction



The Nobel Prize in Physics 2000

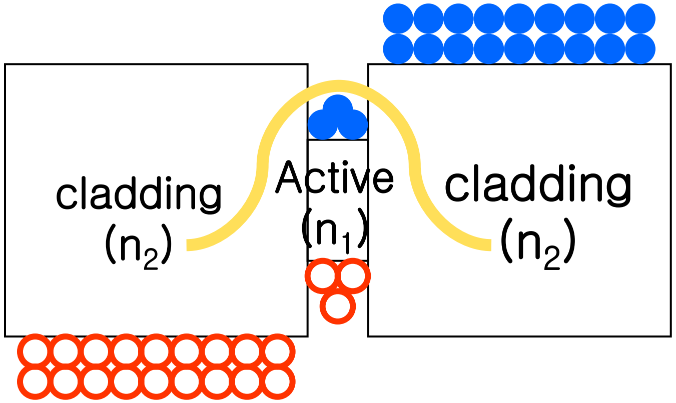
Zhores I. Alferov
Prize share: 1/4

Herbert Kroemer
Prize share: 1/4

The Nobel Prize in Physics 2000 was awarded to Zhores I. Alferov and Herbert Kroemer *"for developing semiconductor heterostructures used in high-speed- and opto-electronics"*

Lect. 24: Semiconductor Lasers

Efficient photon confinement: PIN structure with smaller n for P, N regions



Smaller E_g material has larger n (n_1>n_2)

➔ Dielectric waveguide!

=> More photons interacting with injected electrons and holes in the active region

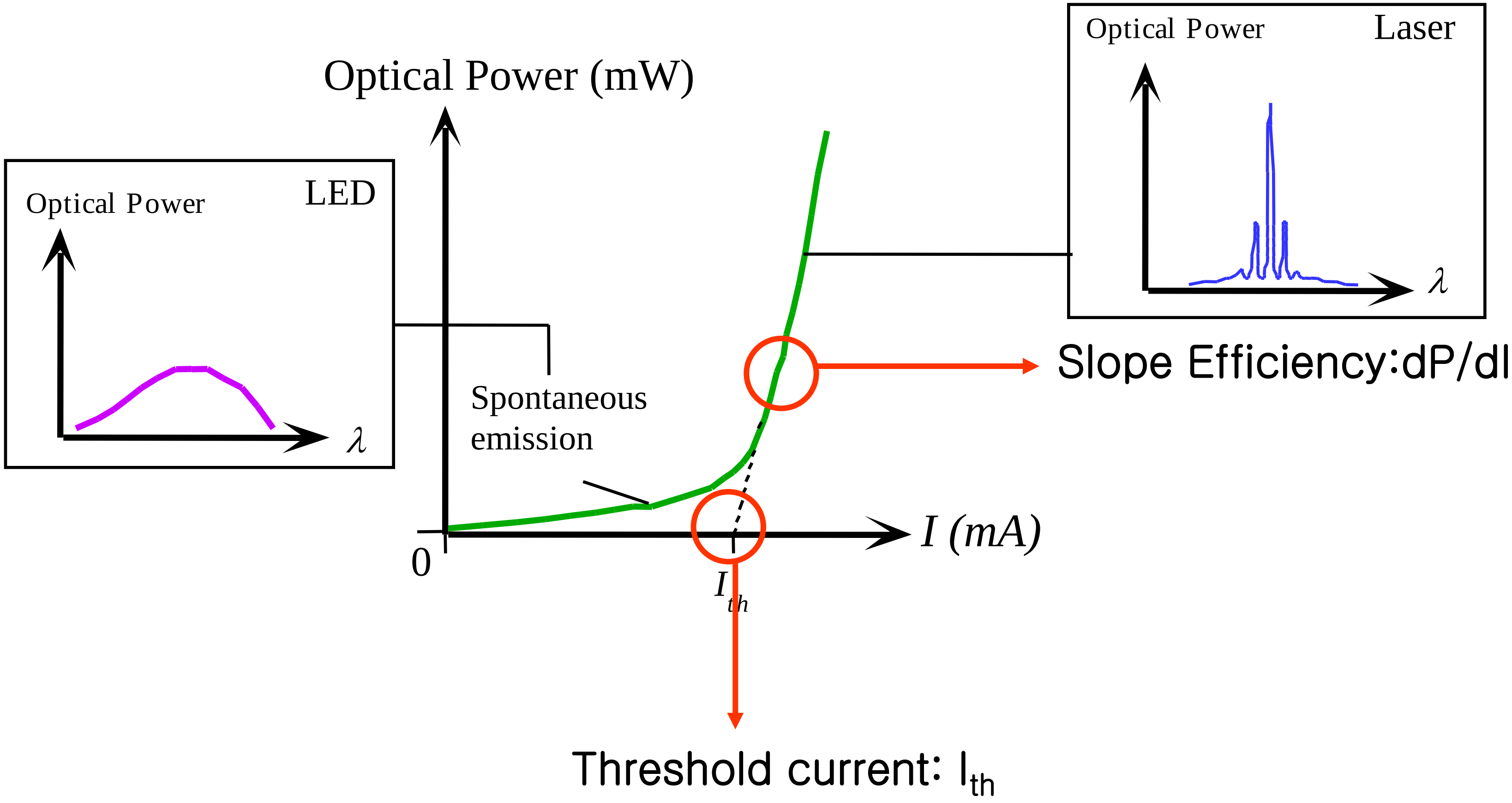
➔ larger Γ

With Γ<1,

$$g_{\mathrm{th}} = \frac{1}{L}\ln\frac{1}{R} = \alpha_{\mathrm{m}}\,(\text{mirror loss}) \quad \Rightarrow \Gamma g_{\mathrm{th}} = \frac{1}{L}\ln\frac{1}{R} = \alpha_{\mathrm{m}}$$

$$\frac{\lambda}{n} = \frac{2L}{m} \quad \Longrightarrow \frac{\lambda}{n_{\mathrm{eff}}} = \frac{2L}{m}; \quad n_{\mathrm{eff}} = \frac{\beta}{k_0}$$

Lect. 24: Semiconductor Lasers



Slope Efficiency:dP/dI

Threshold current: I_{th}

Lect. 24: Semiconductor Lasers

Analytical expression for I_{th}

Assume optical gain increases linearly with injected carriers: $g = a(N - N_0)$

1) Determine carrier density (N_{th}) required for g_{th}:

$$N_{th} = \frac{g_{th}}{a} + N_0, \quad g_{\mathrm{th}} = \frac{\alpha_{\mathrm{m}}}{\Gamma} \quad \therefore \; N_{th} = \frac{\alpha_{\mathrm{m}}}{\Gamma a} + N_0$$

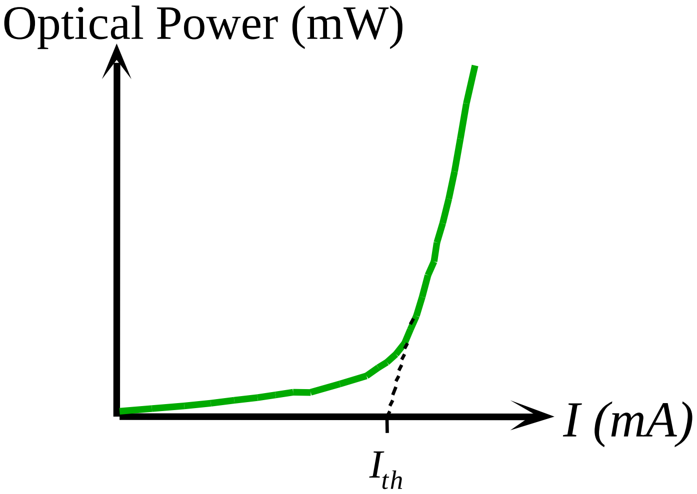
2) Relatioship between I and N

$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau} \qquad \text{In steady-state, } I = \frac{N}{\tau} \cdot qV$$

(V : volume of active region, τ : carrier life time)

3) Determine I_{th} from N_{th} assuming steady-state

$$\therefore I_{th} = \frac{N_{th}}{\tau} \cdot qV = \left(\frac{\alpha_{\mathrm{m}}}{\Gamma a} + N_0\right)\frac{1}{\tau} \cdot qV$$



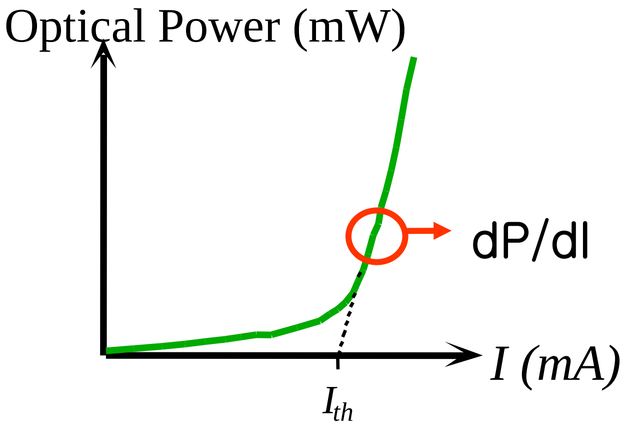
Lect. 24: Semiconductor Lasers

Analytical expression for dP/dI

–Assume injected carriers are all converted into photons by stimulated emission when $I > I_{th}$

– Change in photon density with time

$$\frac{dn_{ph}}{dt} = \frac{I - I_{th}}{qV} - \frac{n_{ph}}{\tau_{ph}} \qquad \tau_{ph} = \frac{1}{v \cdot \alpha_m}$$



– At steady-state,

$$n_{ph} = \frac{I - I_{th}}{qV} \cdot \tau_{ph}$$

– How many photons out of laser per second? $\Longrightarrow \dfrac{n_{ph}V}{\tau_{ph}}$

– Output power

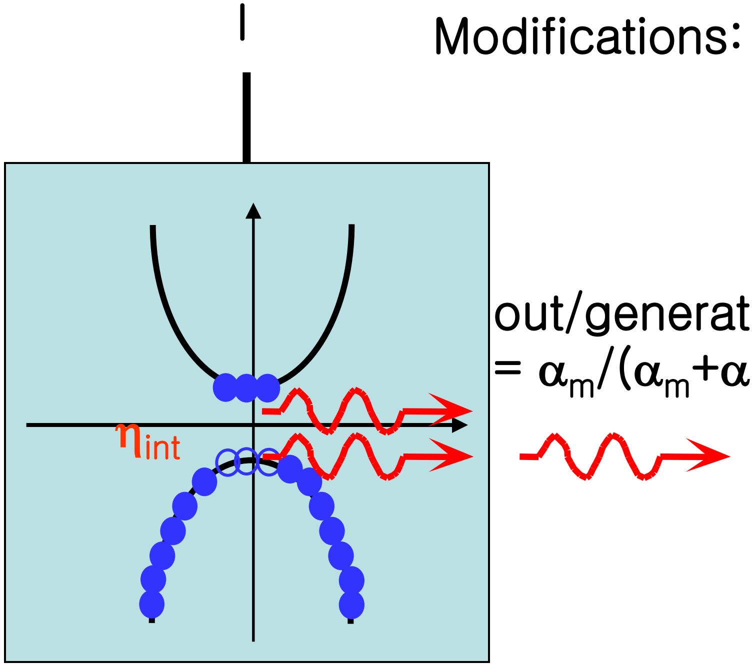
$$P_{out} = \frac{\hbar\omega n_{ph} V}{\tau_{ph}} = \hbar\omega \frac{I - I_{th}}{qV} \cdot \tau_{ph} \frac{V}{\tau_{ph}} = \hbar\omega \frac{I - I_{th}}{q} \quad \therefore \frac{dP}{dI} = \frac{\hbar\omega}{q}$$

Lect. 24: Semiconductor Lasers

More detailed model:

- Injected carriers are not 100% converted into photons: conversion efficiency, η_{int}
- Photons can be lost internally by impurities, scattering, … : internal loss, α_{int}

Modifications:



out/generation = $\alpha_m/(\alpha_m+\alpha_{int})$

$$g_{th} : \frac{\alpha_m}{\Gamma} \quad ==> \quad \frac{\alpha_m+\alpha_{int}}{\Gamma} \qquad I_{th} = \left(\frac{\alpha_m+\alpha_{int}}{\Gamma a} + N_0\right)\frac{1}{\tau}\cdot qV$$

$$n_{ph} : \frac{I-I_{th}}{qV}\cdot\tau_{ph} \quad ==> \quad \eta_{int}\frac{I-I_{th}}{qV}\cdot\tau_{ph}$$

$$\tau_{ph} = \frac{1}{v\cdot\alpha_m} \quad ==> \quad \frac{1}{v\cdot(\alpha_m+\alpha_{int})}$$

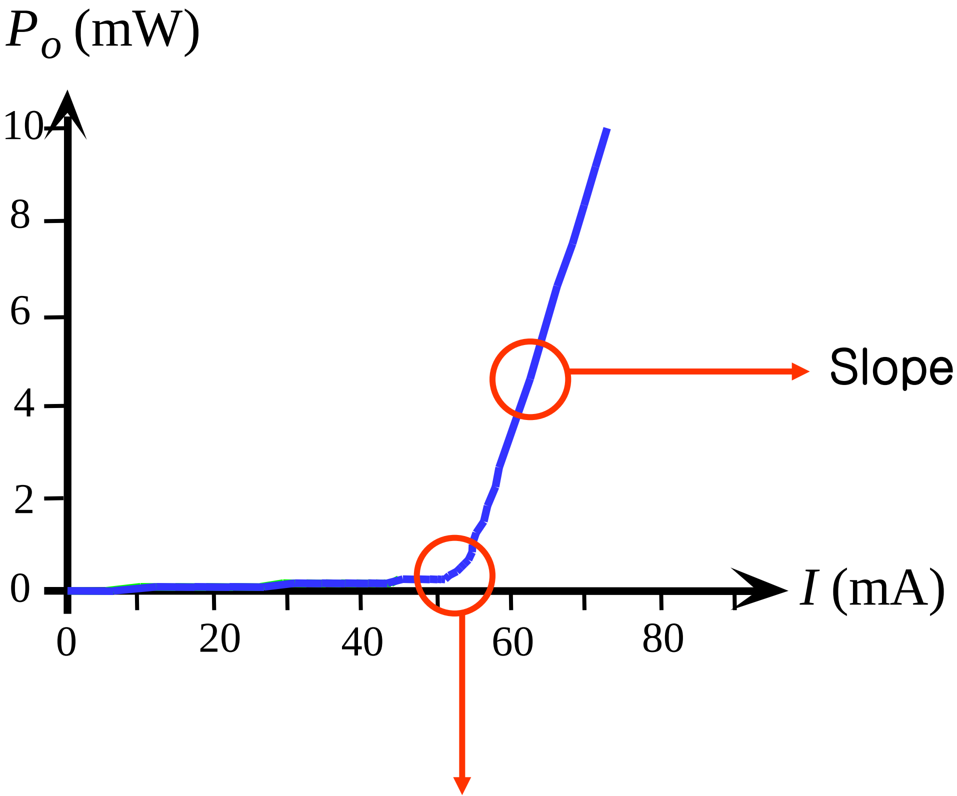
$$P_{out} : \frac{\hbar\omega n_{ph}V}{\tau_{ph}} \quad ==> \quad \frac{\hbar\omega n_{ph}V}{\tau_{ph,m}} \quad \text{with } \tau_{ph,m} = \frac{1}{v\cdot\alpha_m}$$

$$P_{out} = \hbar\omega\cdot\left(\eta_{int}\frac{I-I_{th}}{qV}\tau_{ph}\right)\frac{V}{\tau_{ph,m}} = \frac{\hbar\omega}{q}\cdot\frac{\tau_{ph}}{\tau_{ph,m}}\cdot\eta_{int}(I-I_{th})$$

$$= \frac{\hbar\omega}{q}\frac{\alpha_m}{\alpha_m+\alpha_{int}}\eta_{int}(I-I_{th})$$

$$I_{th} = \left(\frac{\alpha_m}{\Gamma a} + N_0\right)\frac{1}{\tau}\cdot qV \quad ==> \quad \left(\frac{\alpha_m+\alpha_{int}}{\Gamma a} + N_0\right)\frac{1}{\tau}\cdot qV$$

Lect. 24: Semiconductor Lasers



Slope Efficiency:

$$\frac{\mathrm{dP}}{\mathrm{dI}} = \frac{\hbar\omega}{q}\frac{\alpha_{\mathrm{m}}}{\alpha_{\mathrm{m}}+\alpha_{\mathrm{int}}}\eta_{\mathrm{int}}$$

$$\eta_{\mathrm{ext}} = \frac{\alpha_{\mathrm{m}}}{\alpha_{\mathrm{m}}+\alpha_{\mathrm{int}}}\eta_{\mathrm{int}}$$

Threshold current: $$I_{th} = \left(\frac{\alpha_{\mathrm{m}}+\alpha_{\mathrm{int}}}{\Gamma a} + N_0\right)\frac{1}{\tau}\cdot qV$$

Lect. 24: Semiconductor Lasers

Homework:

A semiconductor laser has following properties.

- Cavity length: 500 µm
- Active region width: 2 µm
- Internal loss: 6 cm^{-1}
- Effective index: 3.5
- Active region thickness: 0.2 µm
- Confinement factor: 0.15
- Mirror reflectivity (both facets): 0.3
- Carrier lifetime at threshold: 2 nsec

The gain characteristics for the active region material are shown in the figure shown below.

Answer the following questions. Use interpolation when necessary.

(a) What is the threshold gain in cm^{-1} for the laser?

(b) At what wavelength can the first lasing mode be observed?

(c) Estimate the threshold current for the first lasing mode.

(d) As the injected current increases, more than one lasing modes are observed. What is the mode separation in nm?

Lect. 24: Semiconductor Lasers

Homework: