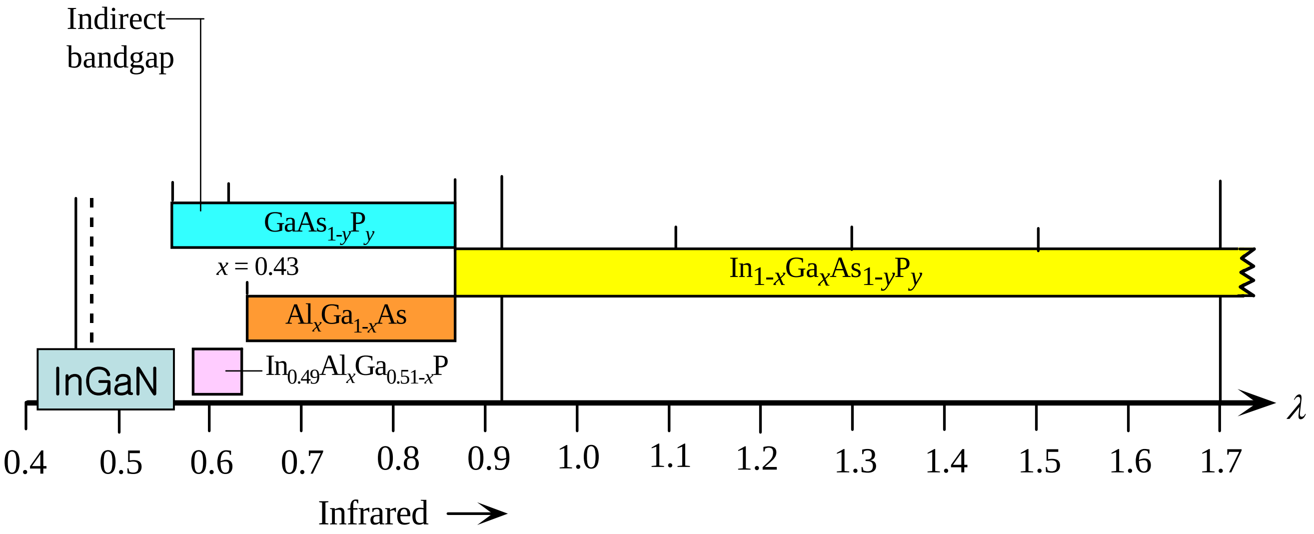
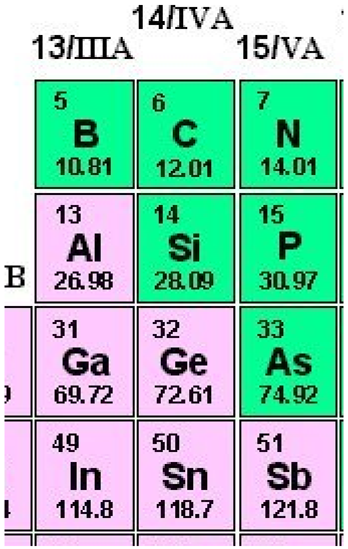
Lect. 22: Semiconductor Lasers

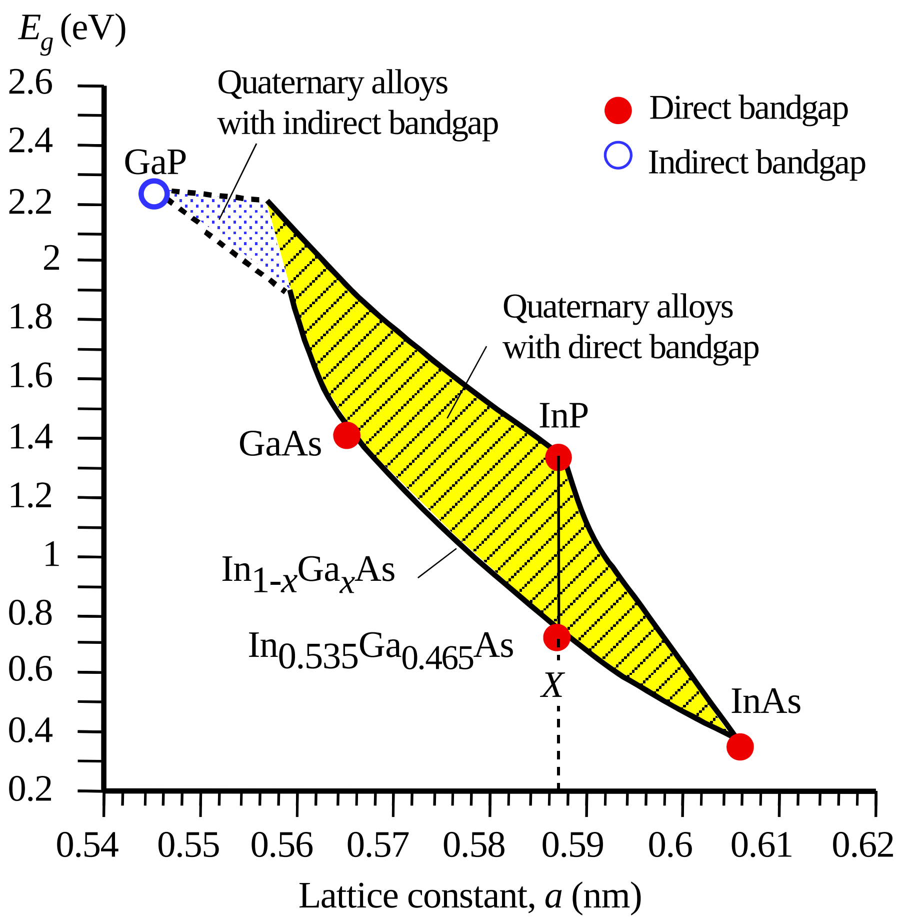
- Semiconductors lasers are small, cheap and very efficient.
- Wavelength: Bandgap of direct semiconductor materials (III-V compound semiconductors)





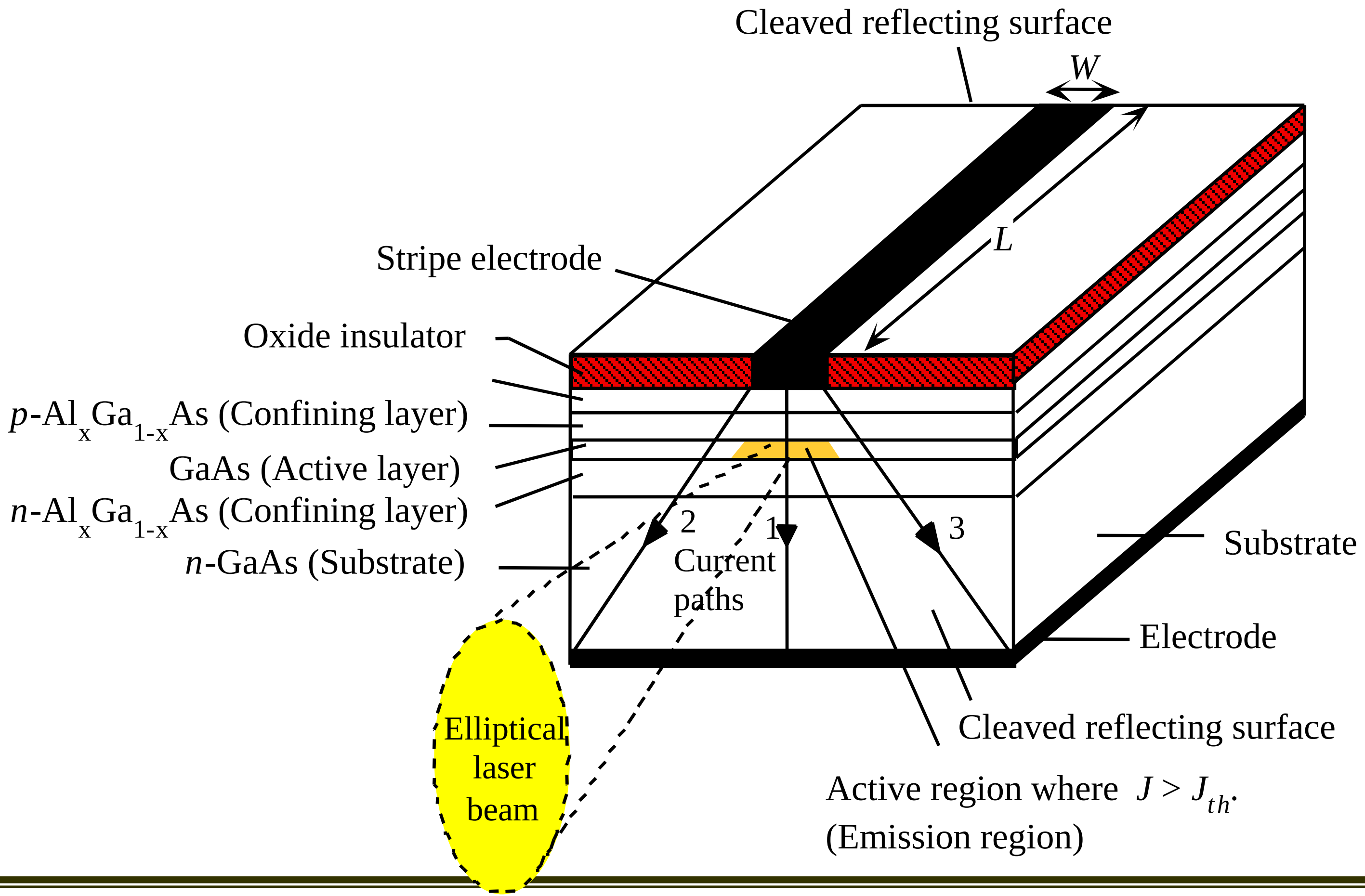
13/IIIA	14/IVA	15/VA
5 B 10.81	6 C 12.01	7 N 14.01
13 Al 26.98	14 Si 28.09	15 P 30.97
31 Ga 69.72	32 Ge 72.61	33 As 74.92
49 In 114.8	50 Sn 118.7	51 Sb 121.8

Lect. 22: Semiconductor Lasers



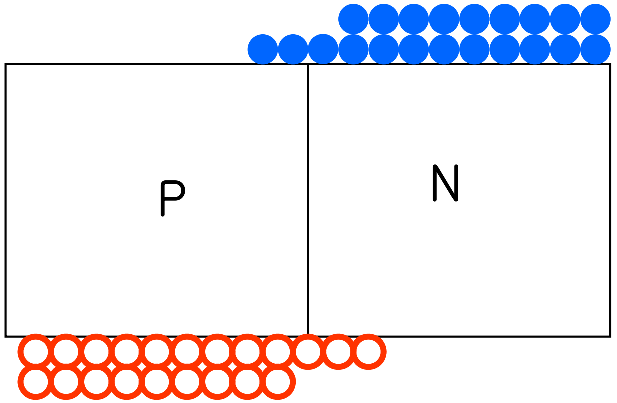
Lect. 22: Semiconductor Lasers

Semiconductor Laser Structure: PN Junction + Mirror (Cleaved Facets)

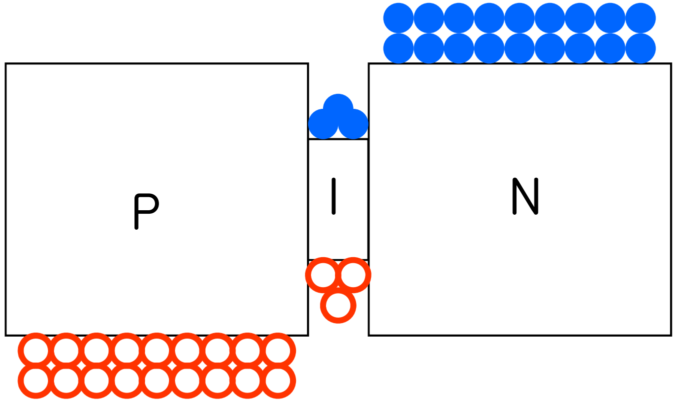


Lect. 22: Semiconductor Lasers

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



Injected carriers are spread-out
=> smaller density

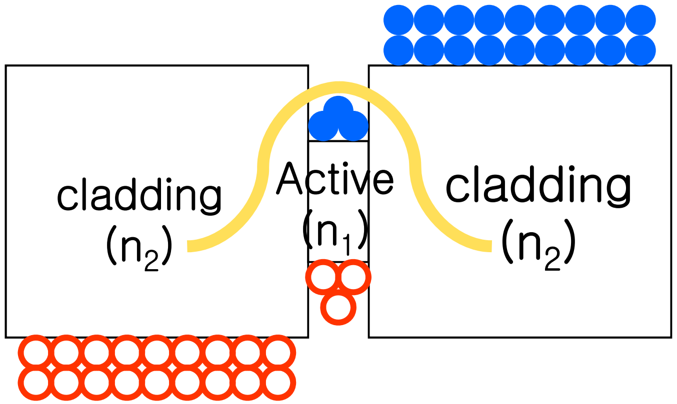


Double heterojunction: Confinement of
Injected carriers
=> larger density

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

Lect. 22: Semiconductor Lasers

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



Smaller E_g material has larger n $(n_1 > n_2)$

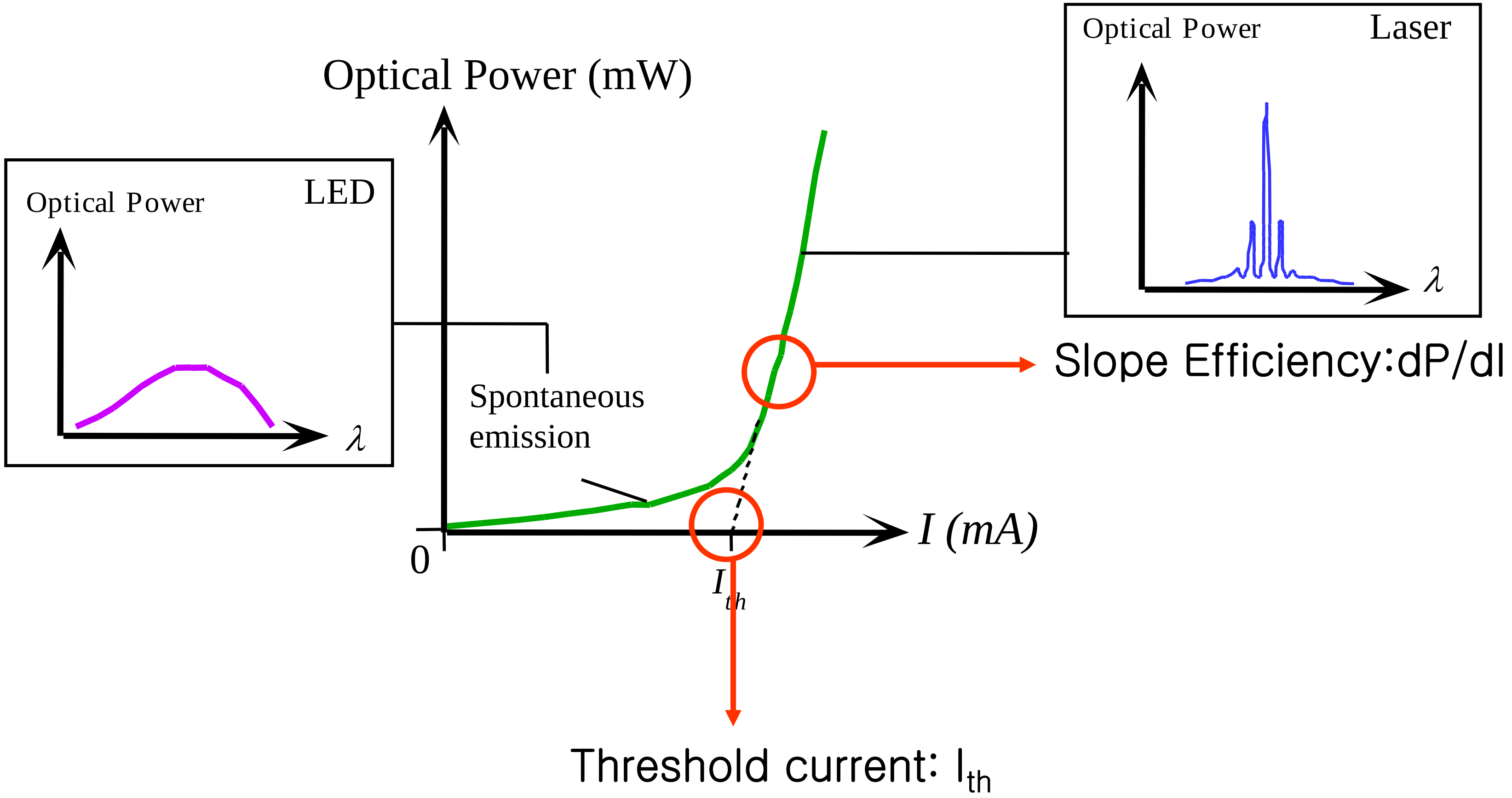
➔ Dielectric waveguide!

=> More photons in the active region and larger Γ

With $\Gamma<1$,

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

Lect. 22: Semiconductor Lasers



Slope Efficiency:dP/dI

Threshold current: I_{th}

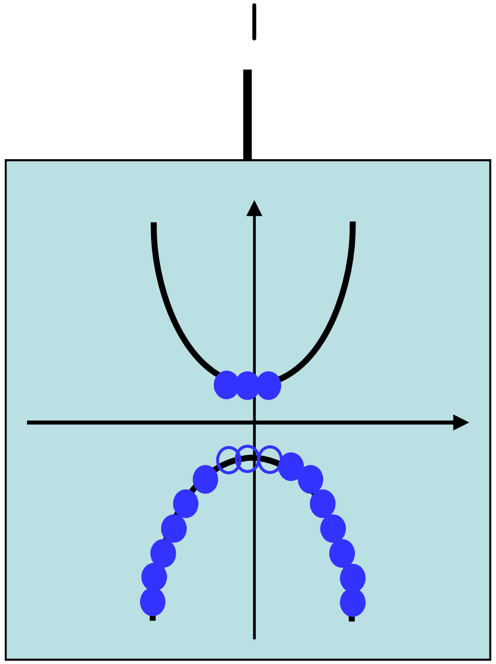
Lect. 22: Semiconductor Lasers

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 lasing:

$$N_{th} = \frac{g_{th}}{a} + N_0 \text{ but } g_{\text{th}} = \frac{\alpha_{\text{m}}}{\Gamma} \quad \therefore\ N_{th} = \frac{\alpha_{\text{m}}}{\Gamma a} + N_0$$



2) Relatioship between I and N

$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau}$$

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

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

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

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

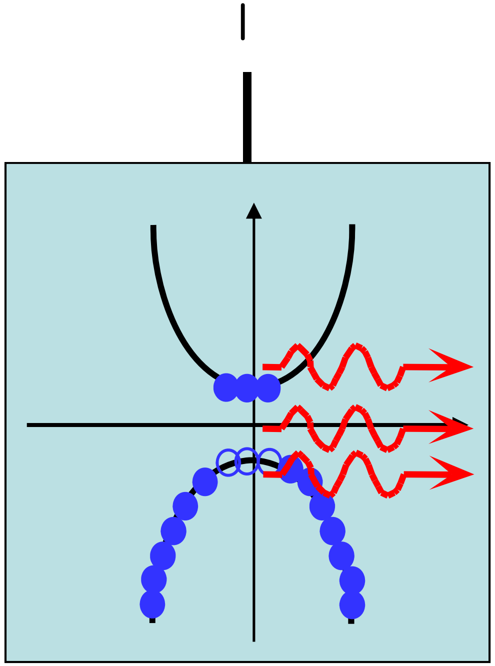
Lect. 22: Semiconductor Lasers

Analytical expression for dP/dI

-Assume injected carriers are all converted into photons by stimulated emission when I>Ith

– Change in photon density with time

$$\frac{dn_{ph}}{dt} = \frac{I - I_{th}}{qV} - \frac{n_{ph}}{\tau_{ph}}; \quad \tau_{ph} = \frac{1}{v \cdot \alpha_{\mathrm{m}}}$$



– At steady-state,

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

– Output power

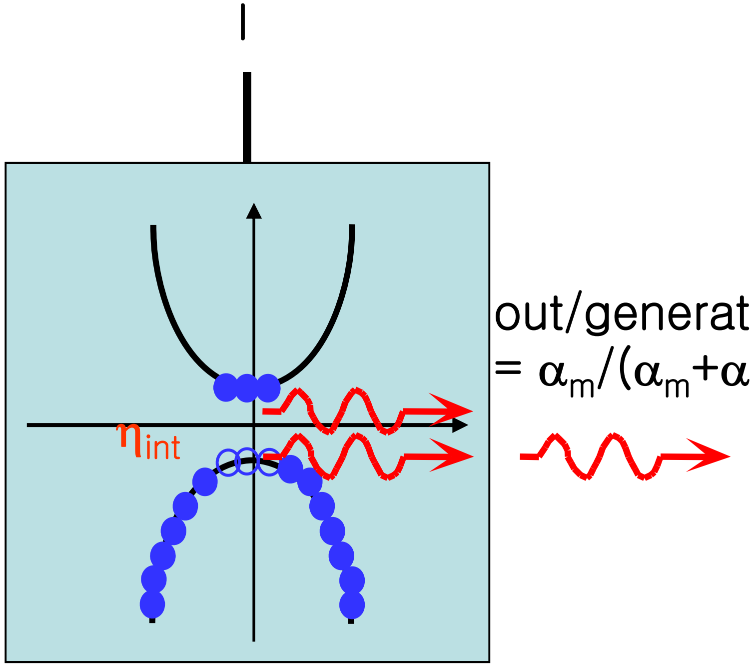
$$P_{out} = \frac{\hbar\omega n_{ph} V}{\tau_{ph}} = \hbar\omega \frac{I - I_{th}}{qV} \cdot \tau_{ph} \frac{V}{\tau_{ph}} = \hbar\omega \frac{I - I_{th}}{q}$$

Lect. 22: Semiconductor Lasers

Refinements:

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

Modifications:



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

$$g_{th} = \frac{\alpha_m + \alpha_{int}}{\Gamma}$$

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

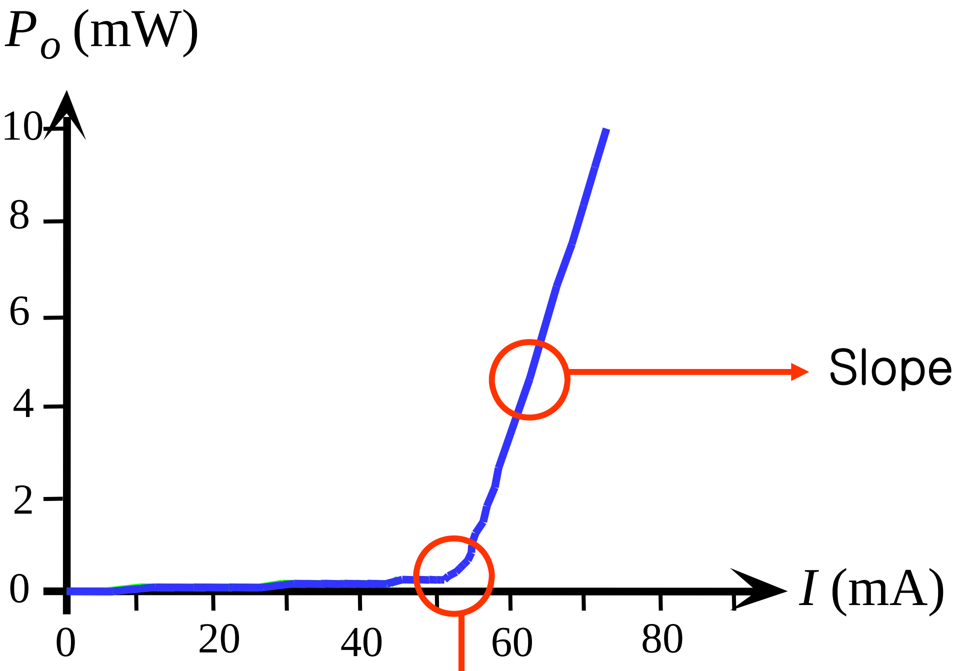
$$\tau_{ph} = \frac{1}{v\cdot(\alpha_m + \alpha_{int})} \text{ and } \tau_{ph,m} = \frac{1}{v\cdot\alpha_m}$$

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

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

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

Lect. 22: Semiconductor Lasers



Slope Efficiency:

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

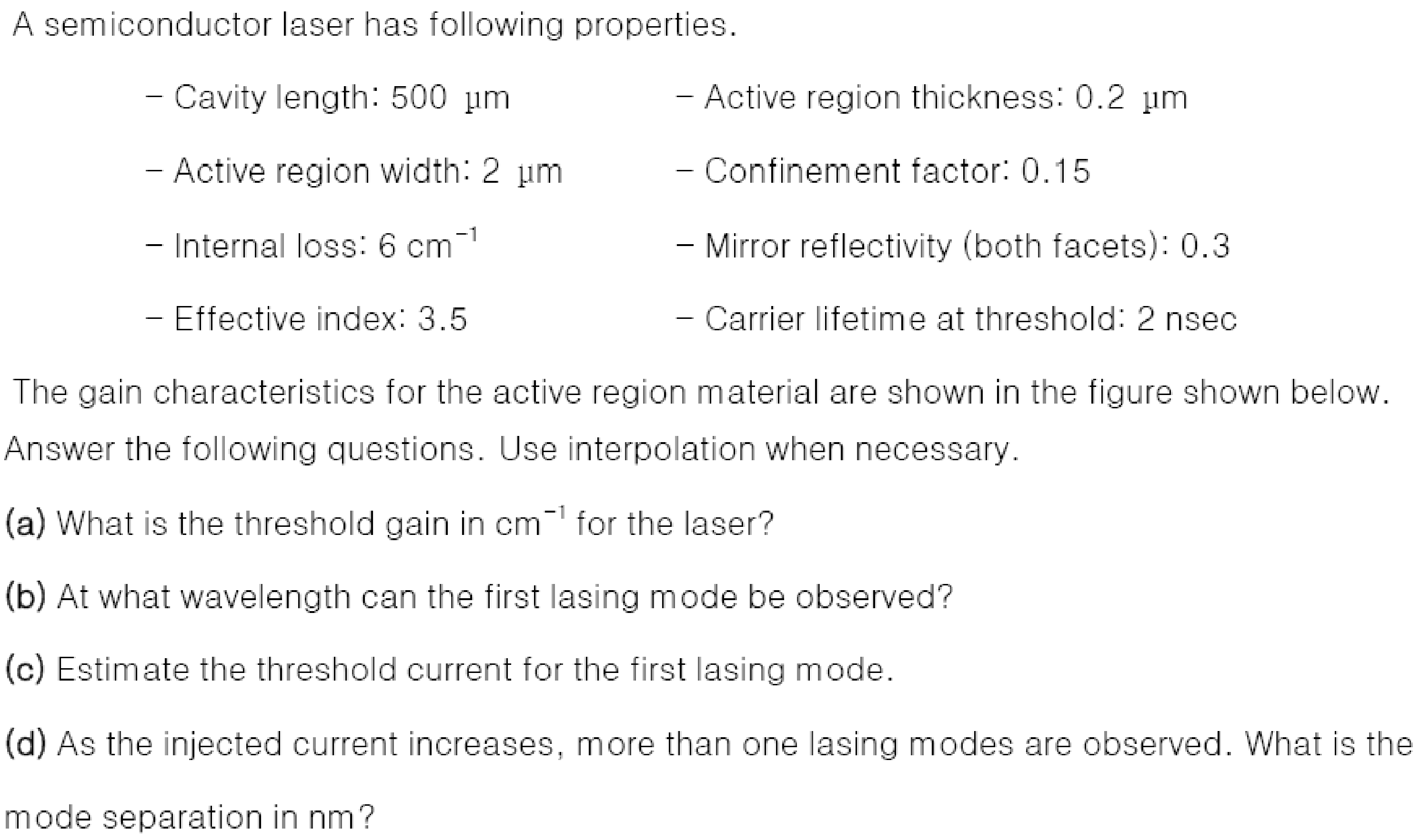
$$\eta_{\mathrm{ext}} = \frac{\alpha_{\mathrm{m}}}{\alpha_{\mathrm{m}}+\alpha_{\mathrm{int}}}\eta_{\mathrm{int}}$$

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

Homework: Prob. 1 in 2002 Test 3

Lect. 22: Semiconductor Lasers

Homework (Due Nov. 22): Prob. 2 in 2001 Test 3



A semiconductor laser has following properties.

- Cavity length: 500 µm
- Active region thickness: 0.2 µm
- Active region width: 2 µm
- Confinement factor: 0.15
- Internal loss: 6 cm^{-1}
- Mirror reflectivity (both facets): 0.3
- Effective index: 3.5
- 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. 22: Semiconductor Lasers

Homework (Due Nov. 22): Prob. 2 in 2001 Test 3