

Topic 14

14 Semiconductor laser diodes

14.1 Introduction

14.2 Requirements for a laser diode

14.3 Laser structure

14.4 Gain and loss

14.5 Optical confinement and threshold

14.5 Design laser diode

14.6 Examples of semiconductor laser diode

Introduction (i)

- WDM system requires an optical source with a **high modulation speed** and a **narrow line width**
- Major advantages of LDs over LEDs:

(1) **Modulation speed** (lifetime of minority carriers)

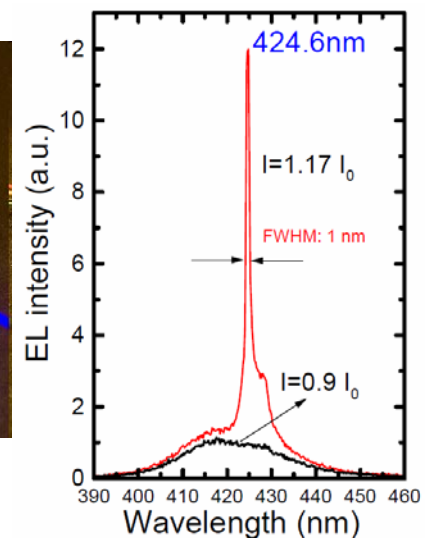
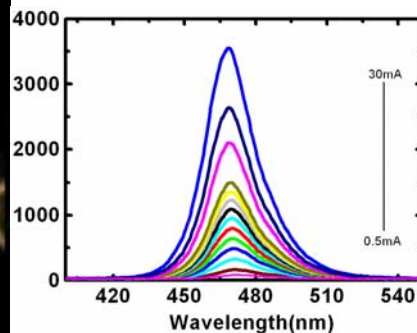
LD: $f \sim 1/\tau_{\text{stim}}, \tau_{\text{stim}} \sim 10\text{ps}, f \sim 100\text{GHz}$

LED: $f \sim 1/\tau_{\text{spont}}, \tau_{\text{spont}} \sim 10\text{ns}, f \sim 100\text{MHz}$

(2) **FWHM**

LEDs: $\sim 100\text{nm}$

LDs: FP Laser ($\sim 1\text{nm}$); DFB Laser ($\sim 0.0001\text{nm}$); VCSEL laser ($<1\text{ nm}$)



Introduction (ii)

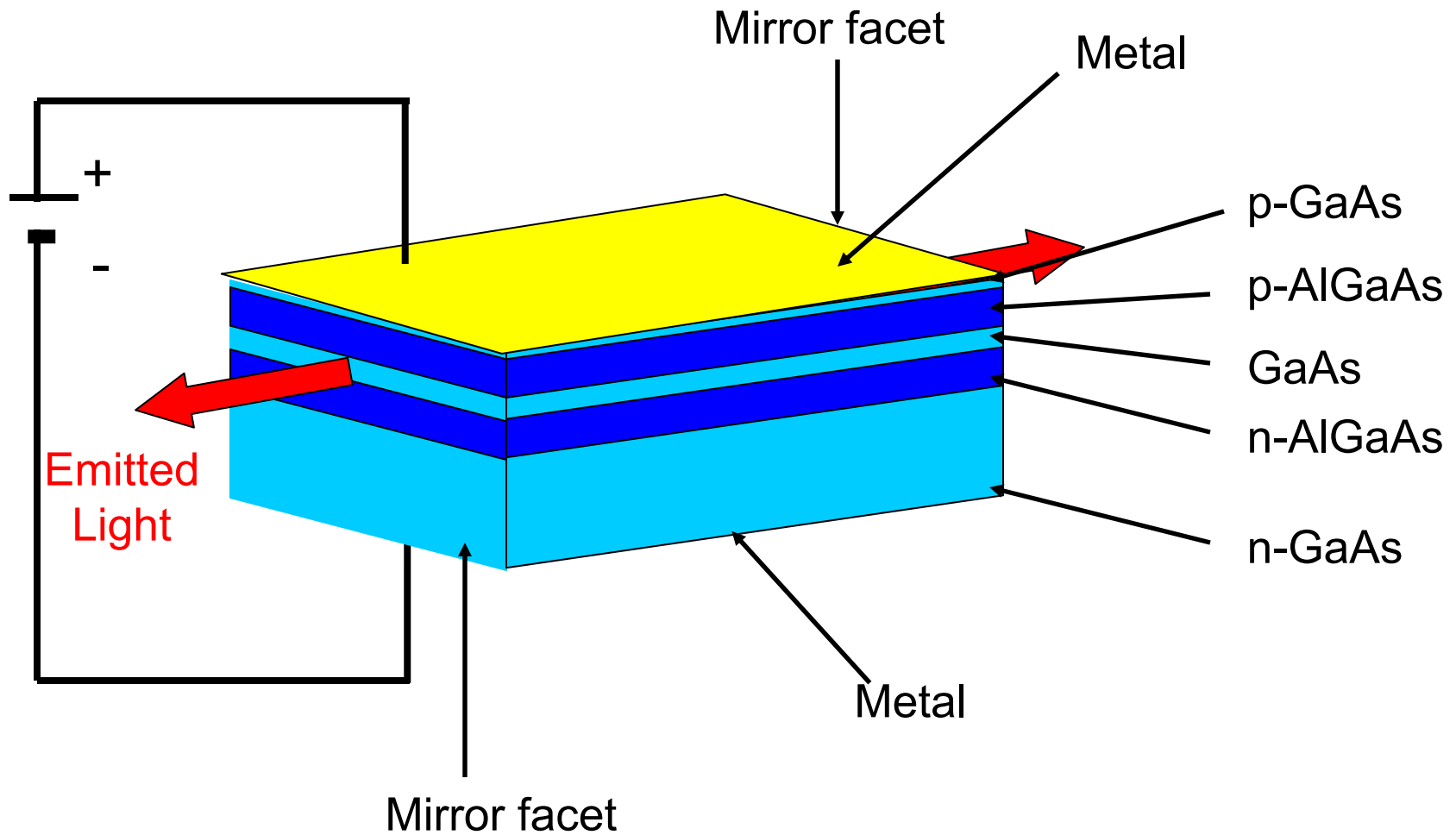
Laser stands for “**L**ight **A**mplification by the **S**timulated **E**mission of **R**adiation”.

Laser: a combination of optical cavity, which provides **feedback** and optical gain region, which provides an **stimulated emission**.

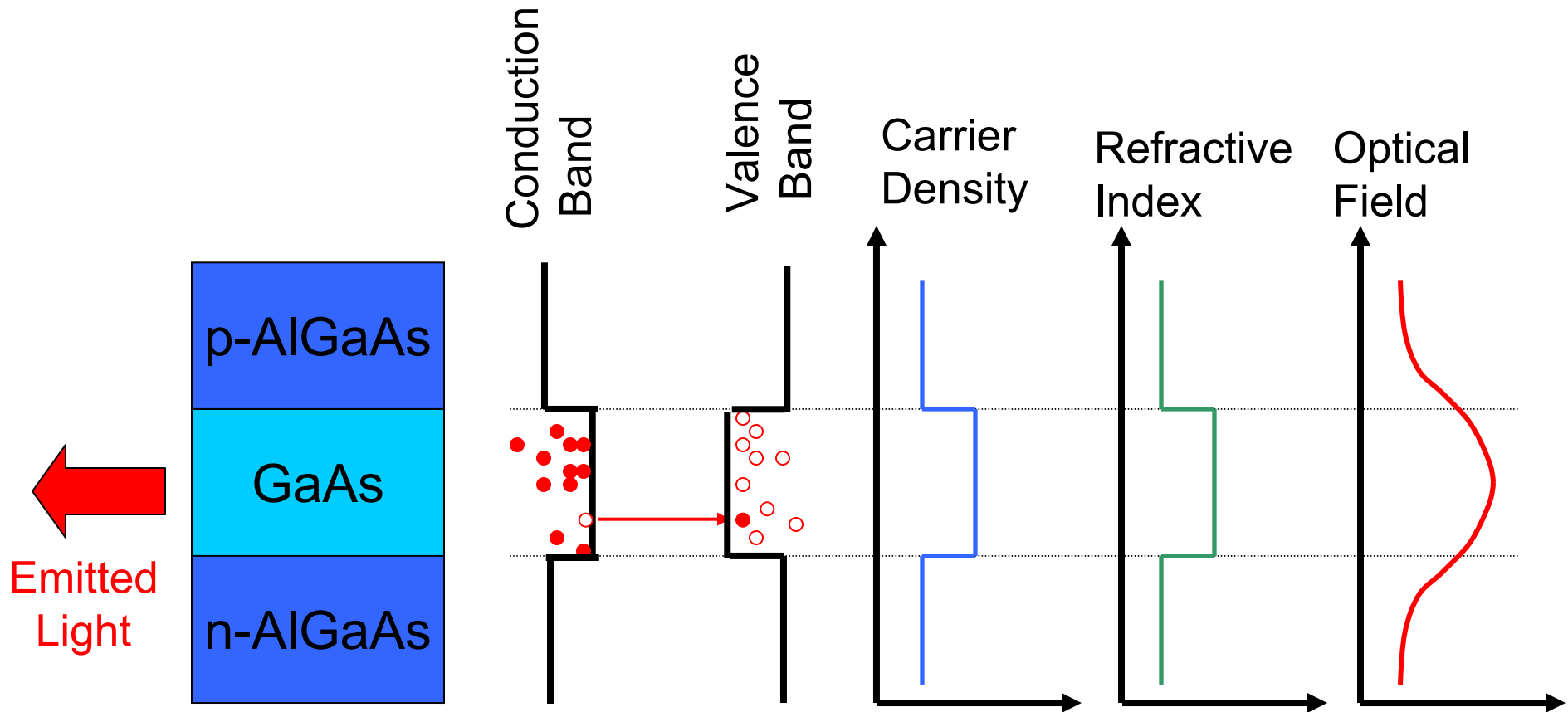
Lasing: takes place when **internal gain**, produced by stimulated recombination of injected carriers, is stronger than the **optical loss**.

The allowed emission wavelengths are those that return **in phase** after a round trip of the optical cavity.

Heterostructure Laser



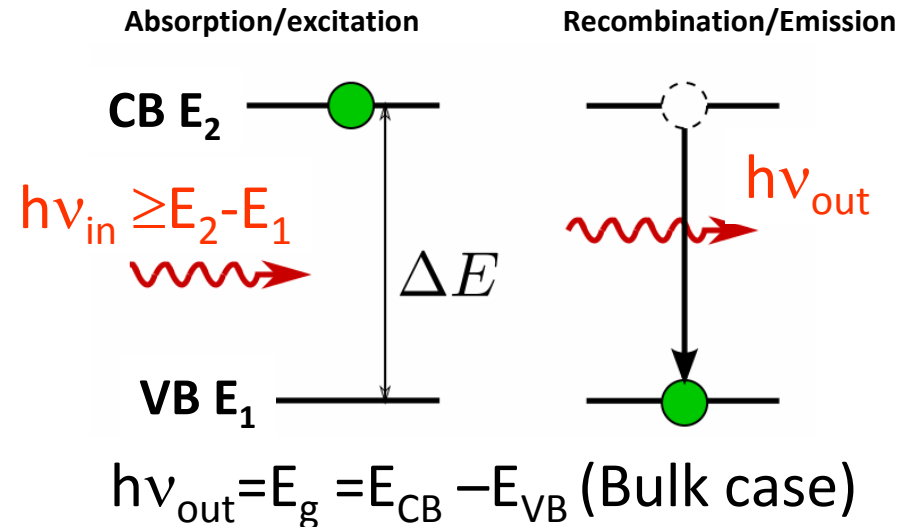
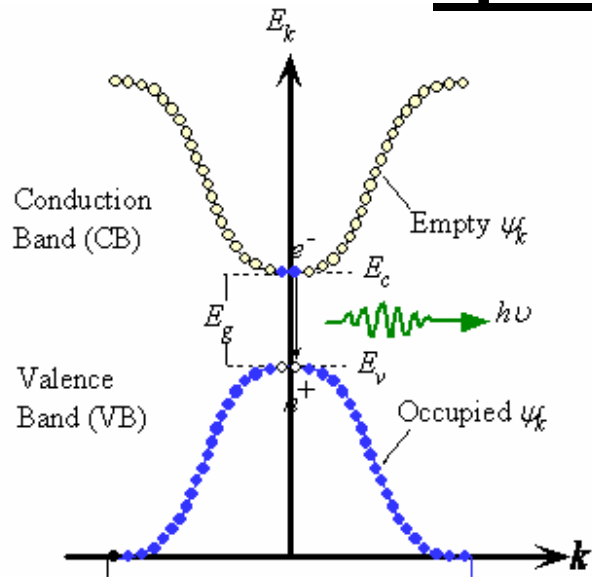
Heterostructure Laser Cross-section



Sandwich structure:

- **Optical confinement:** different refractive indices
- **Carrier confinement:** different band-gaps

Spontaneous Emission



- **Spontaneous emission:**

After an optical or electrical excitation, electrons undergo a transition from VB to CB and then emit a photon.

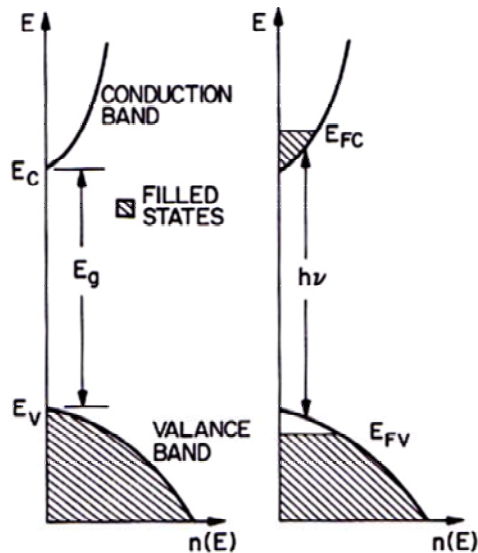
- **Conditions for optical absorption**

(1) $h\nu_{in} \geq E_{CB} - E_{VB}$; (2) Empty states in CB and occupied electrons in VB

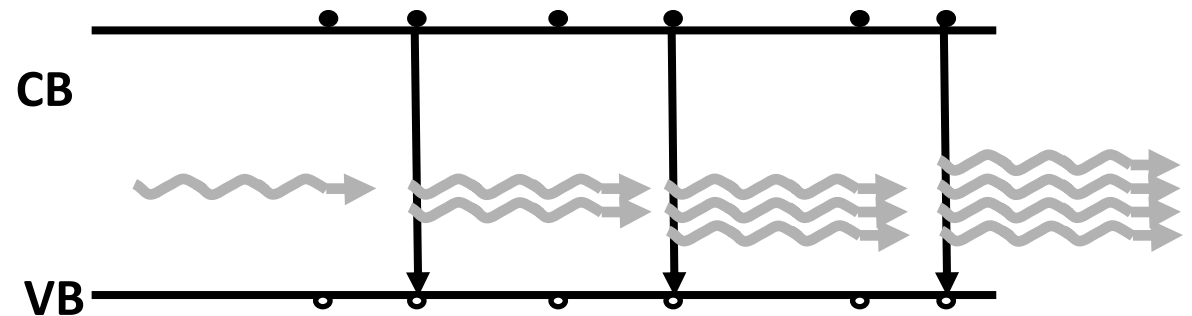
- **Normally, the electron population (N_2) in CB is less than N_1 in VB:**

$N_2/N_1 = \exp(-E_g/KT)$ -----Boltzmann Statistic

- **Photons created via spontaneous emission: random direction and phase**



Stimulated Emission



- **Population inversion:**

More electrons in the CB than electrons in VB

In this case, $E_{Fn} > E_{FP}$

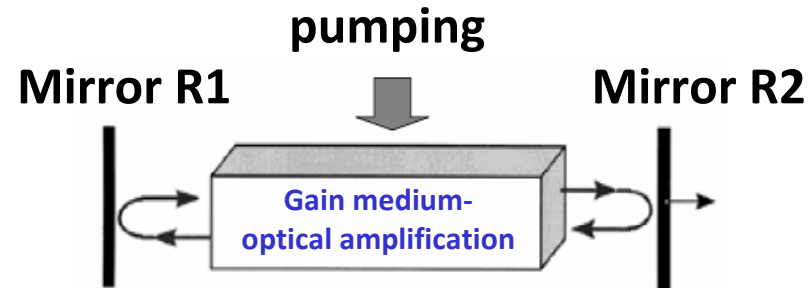
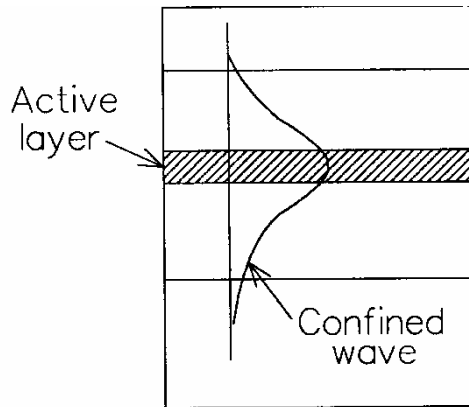
- Any incoming photon with the energy of $E_c - E_v$ cannot be absorbed due to the absence of electrons at E_v . (Transparent conditions)

The photon can stimulate **recombination**, causing an electron to fall down from E_c to E_v . This is stimulated emission. The number of photons with the same energy will exponentially increase. **Optical amplification!**

- Photons created are identical in energy, phase, direction

- The initial stimulus is provided by any spontaneous emission

Optical Feedback



Laser = Gain medium + Cavity

- The emitted light in the active region can be amplified, meaning “obtaining **optical gain**”. However, a **single amplification is not enough**.

⇒ **Optical feedback is necessary: optical cavity**

⇒ Elevate the intensity of stimulated emission

- **Optical cavity:**

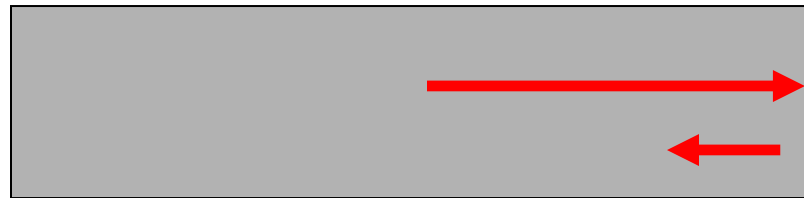
- (1) Provided by the resonator (**F-P cavity**)
- (2) Multiple passes in the medium due to the reflectors: amplification is substantial
- (3) **Gain obtained** in the medium and also **loss** occurring during the optical feedback process
- (4) **Saturation is reached when gain=loss**

Optical Loss due to Fresnel Reflection

Semiconductor $n \sim 3.5$

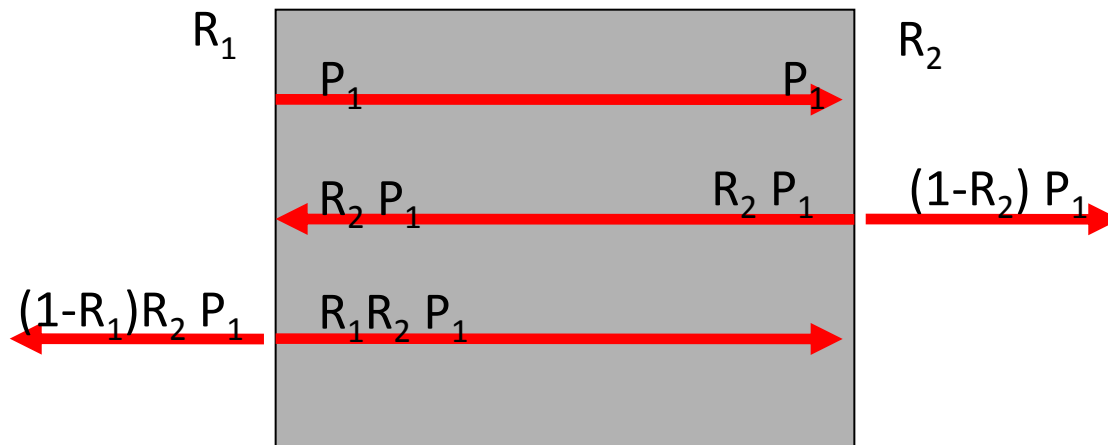
Air $n=1$

Reflected Power



$$I_R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

As Cleaved Semiconductor Facets - Reflectivity **$\sim 30\%$**

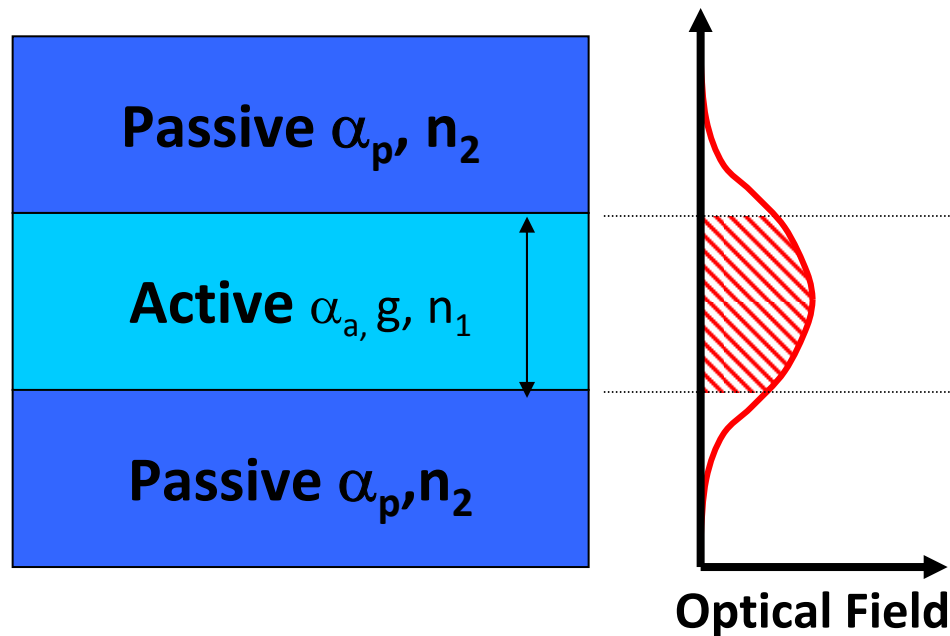


mirror loss

$$\alpha_m = \frac{1}{2l} \ln \frac{1}{R_1 \times R_2}$$

In 1 round trip only **9% of the original power** is left if no any other loss

Optical Confinement (Γ)



- Only in the active region can the light be “amplified”. Therefore, it is important to confine light in active region

- Optical confinement factor Γ : the fraction of the optical field in the gain region

$$\Gamma \cong 1 - e^{-C \cdot \Delta n \cdot d}$$

- Δn : contrast of refractive index
- d : thickness of active region
- C : constant

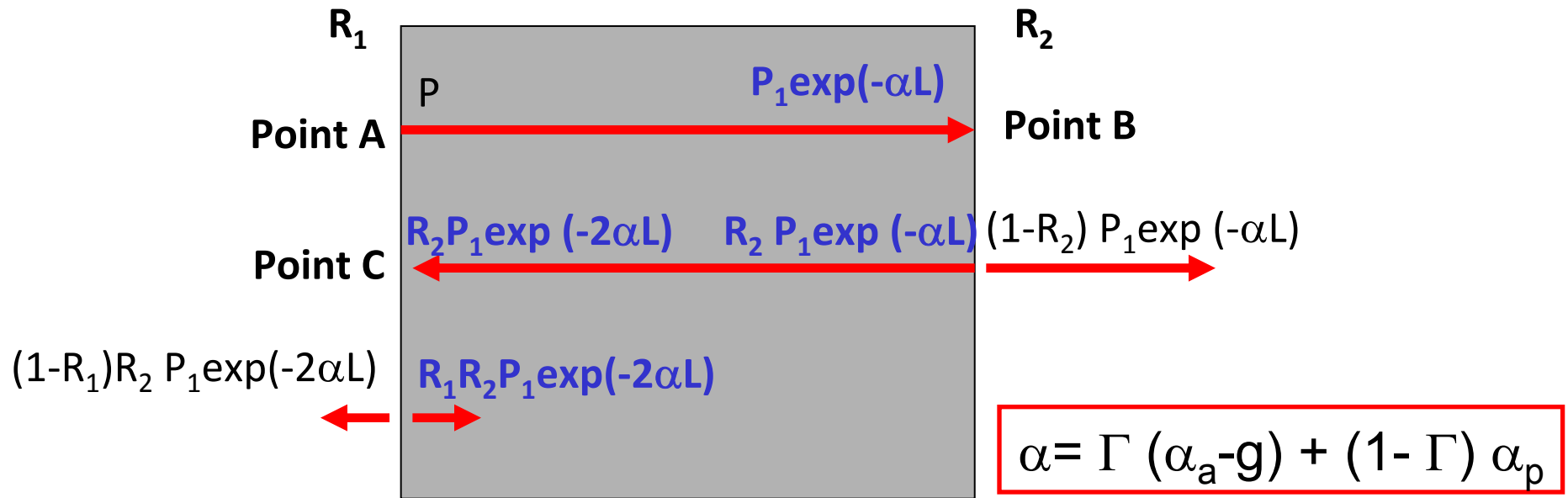
Net loss coefficient: $\alpha = \Gamma (\alpha_a - g) + (1 - \Gamma) \alpha_p$

α_p = passive loss coefficient e.g. free carrier absorption

α_a = active loss coefficient, e.g. scattering at active/passive interface

g = gain in active (“material gain”)

Total Optical Loss in an Optical Cavity



- P undergoes **net loss** $\Rightarrow P \exp(-\alpha L)$
- Undergoes loss due to a **reflector** $\Rightarrow R_2 P \exp(-\alpha L)$
- Under goes another **net loss** $\Rightarrow R_2 P \exp(-2\alpha L)$
- Undergoes another loss due to a **reflector** $\Rightarrow R_1 R_2 P \exp(-2\alpha L)$

After a round trip Gain and loss balance light power will have to be **the same as the initial optical power:** $R_1 R_2 P \exp(-2\alpha L) = P$

Therefore, lasing Condition: $R_1 R_2 \exp(-2L\alpha) = 1$

Threshold Gain

- Previous slides tell you about lasing conditions, and thus the lasing threshold

$$R_1 R_2 \exp(-2L\alpha) = 1$$

- Previous slides also tell you: **Net loss per unit length:**

$$\alpha = \Gamma (\alpha_a - g) + (1 - \Gamma) \alpha_p$$

- We can have

$$\alpha = (1/2L) \ln(R_1 R_2) = \Gamma (\alpha_a - g) + (1 - \Gamma) \alpha_p$$

- **Gain coefficient at the lasing threshold, g_{th} :**

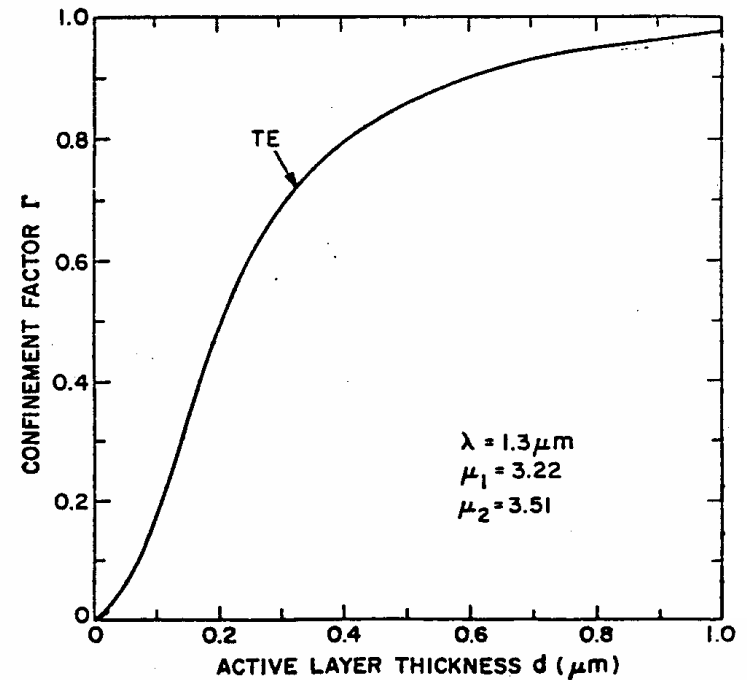
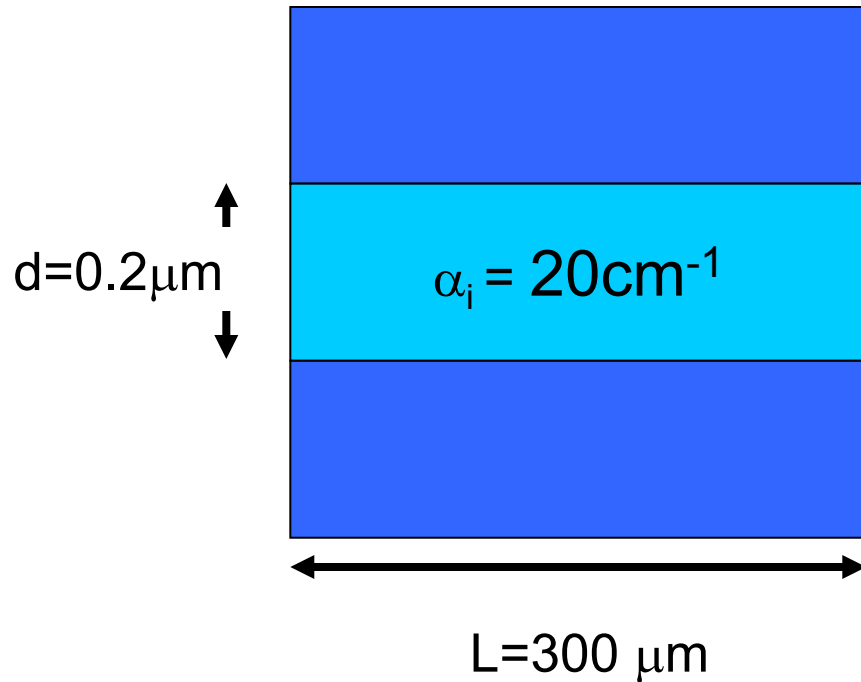
$$g_{th} = \frac{1}{\Gamma} \left[\alpha_i + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right) \right]$$

- where the total **cavity loss** $\alpha_i = \Gamma \alpha_a + (1 - \Gamma) \alpha_p$ and L: cavity length

Typical Values

$$R_1 = R_2 = 0.32$$

For $d=0.2\mu\text{m}$ $\Gamma \sim 0.4$



$$g_{th} = \frac{1}{\Gamma} \left[\alpha_i + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right) \right] \quad (\text{keeping dimensions in cm})$$

$$= 1/0.4 [20 - (1/2 \times 0.03) \ln(0.32)^2] = 2.5 \times [20 + 2.27/0.06] = 2.5 \times 58$$

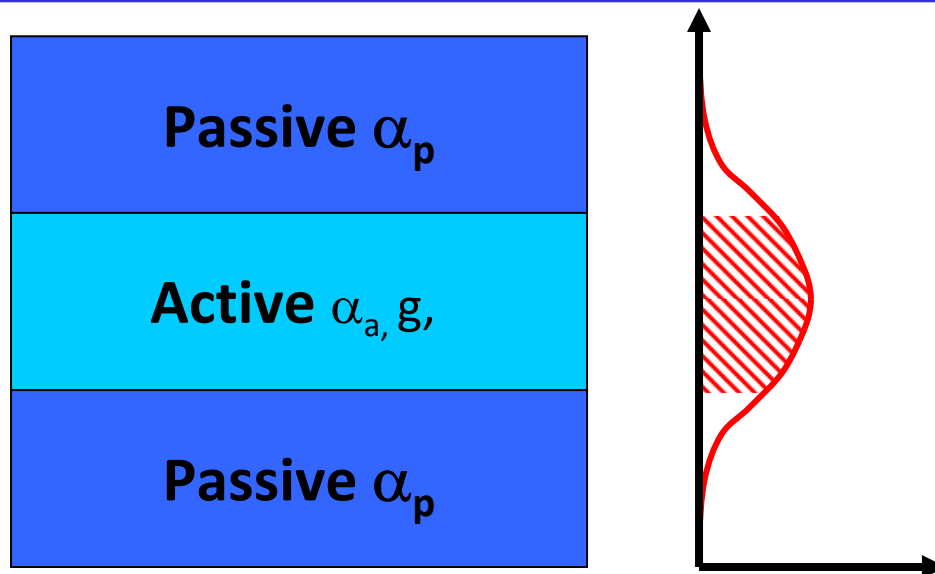
$$g_{th} \sim 150\text{cm}^{-1}$$

Reducing Threshold Gain

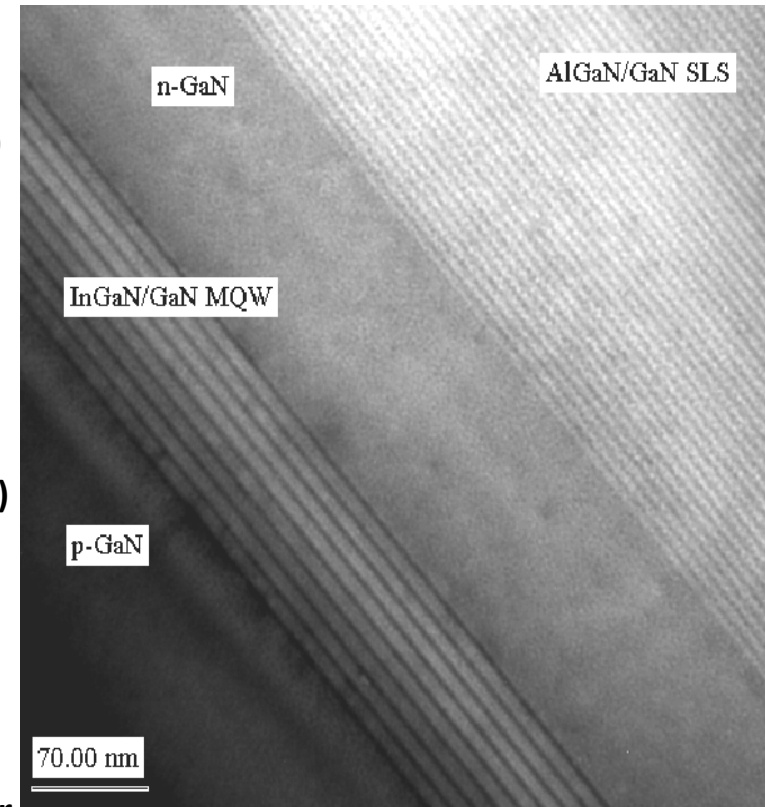
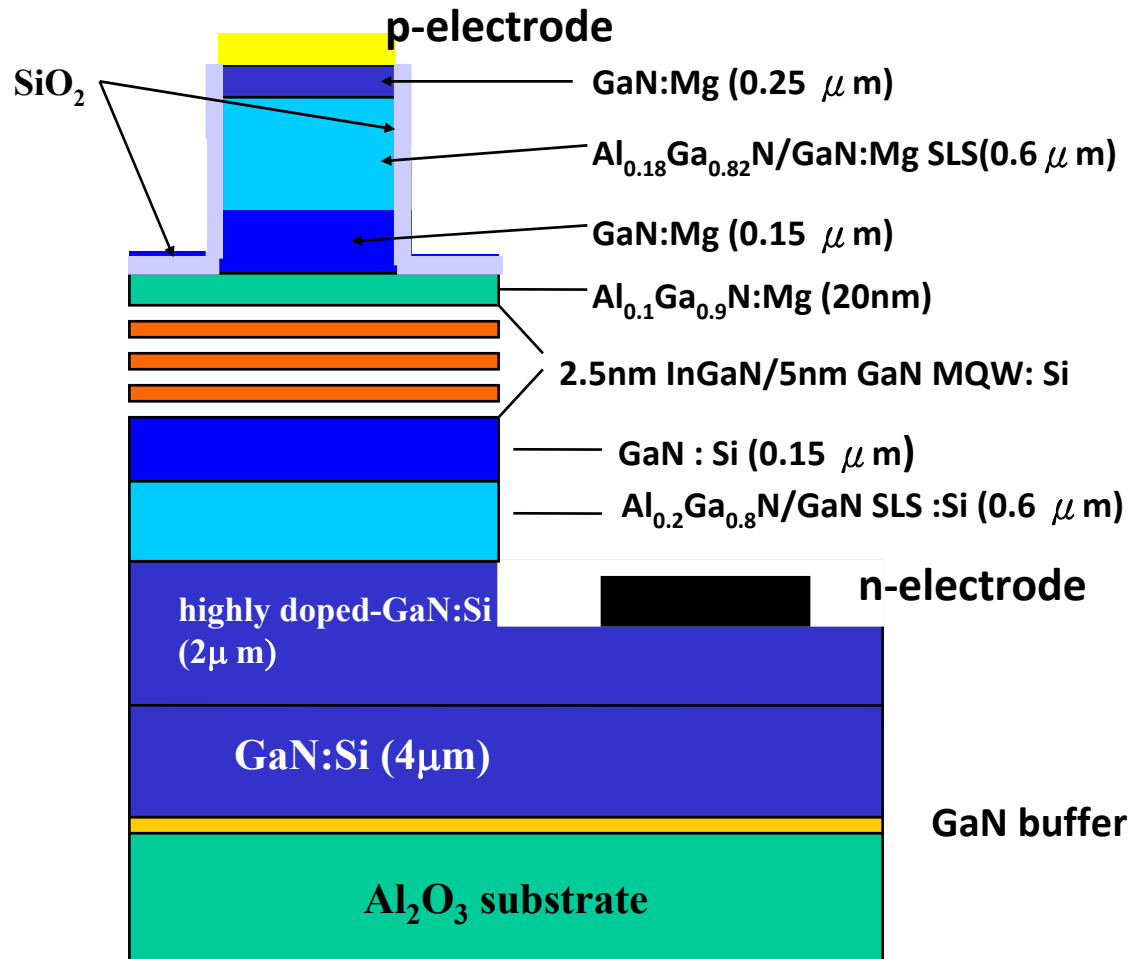
$$g_{th} = \frac{1}{\Gamma} \left[\alpha_i + \frac{1}{2L} \ln\left(\frac{1}{R_1 \cdot R_2}\right) \right]$$

Reduce losses α_a and α_p

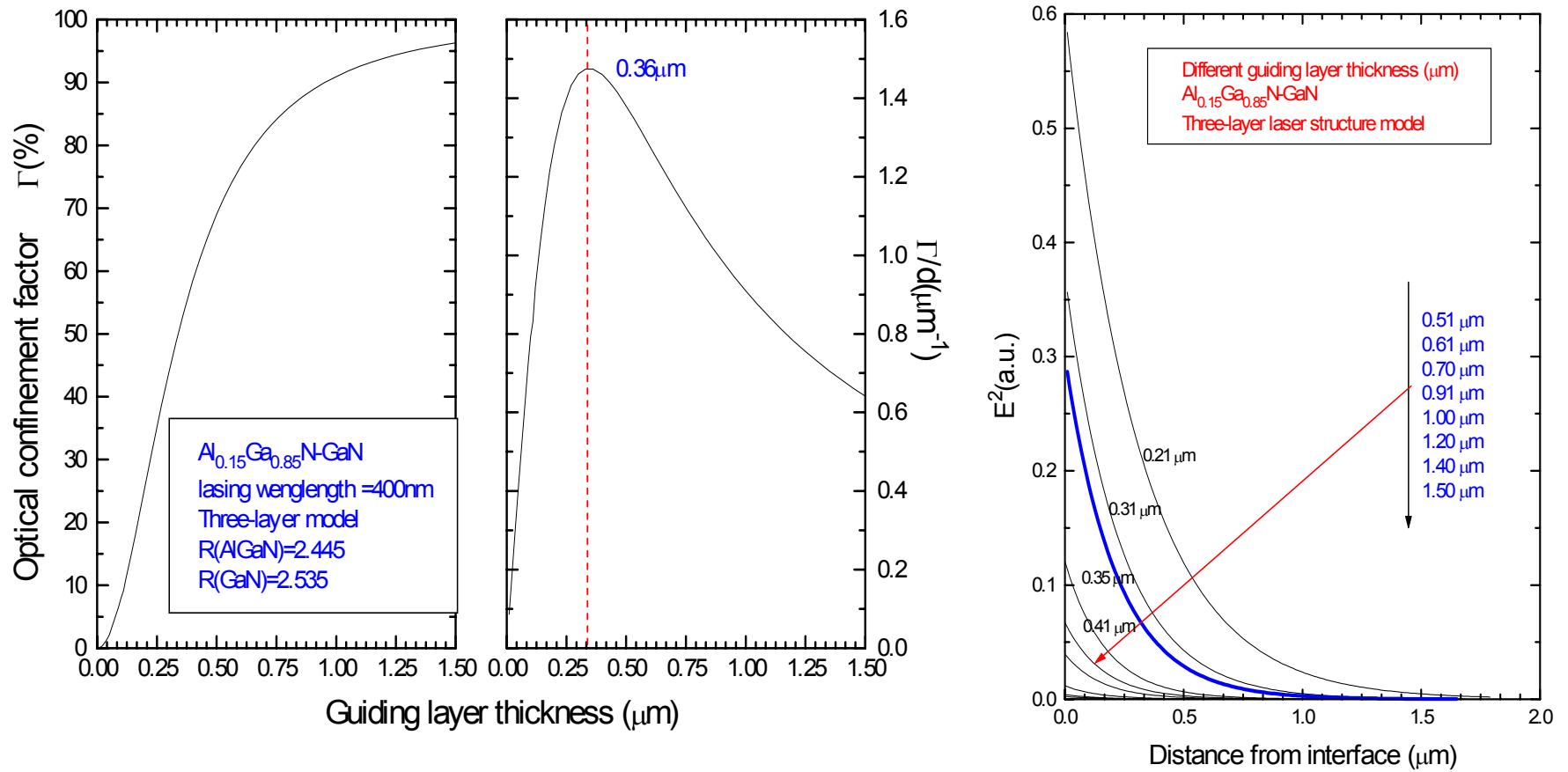
- Increase Γ :
 - (1) increasing **refractive index contrast** in active region and the cladding region
 - (2) Increasing the **cladding layer thickness**
- Increase R_1, R_2 – make one mirror highly reflective - high reflectivity mirror facet: DBR~100%
- Increase L : Be careful, as it also increases loss in practical applications



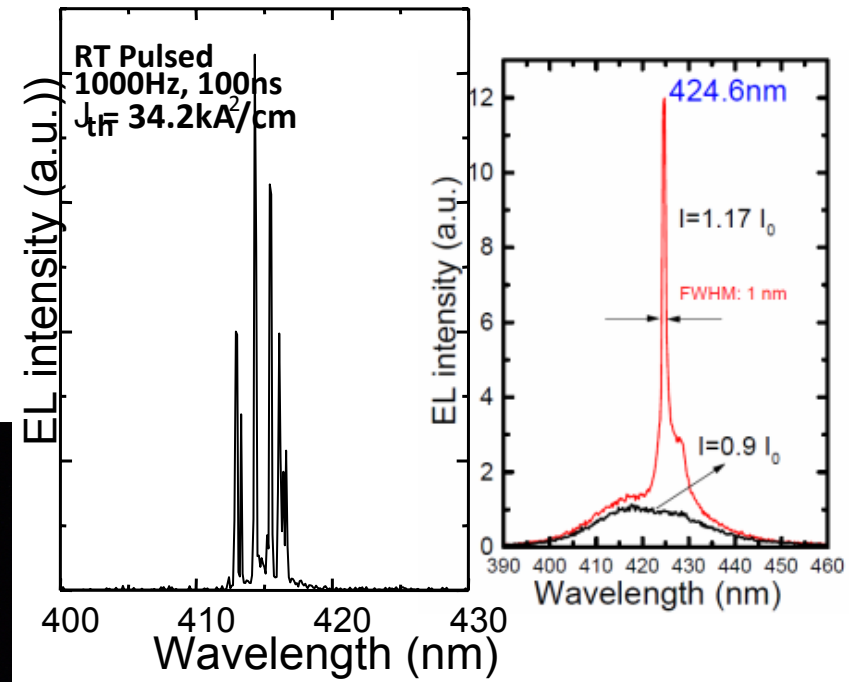
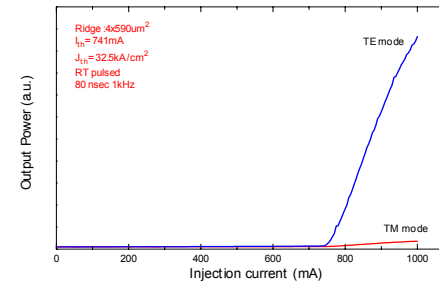
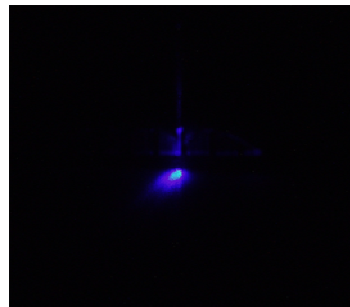
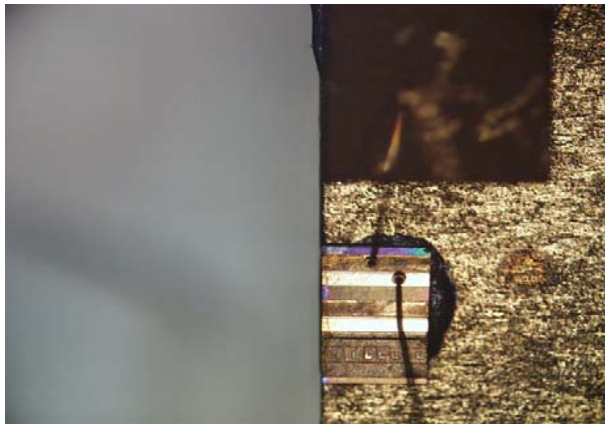
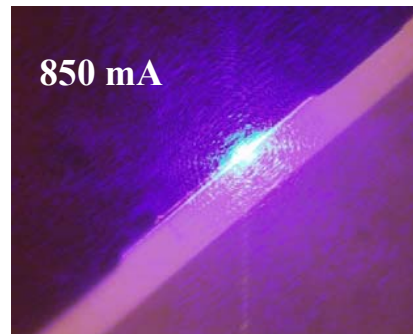
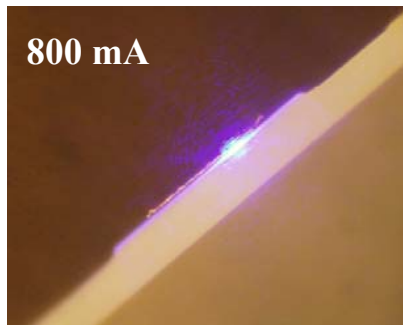
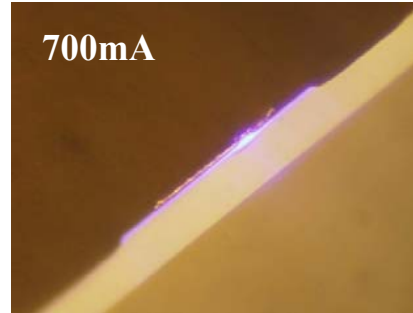
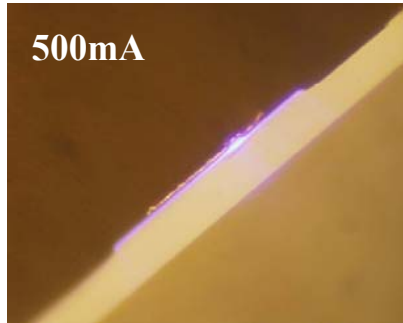
InGaN-based LD as an Example (i)



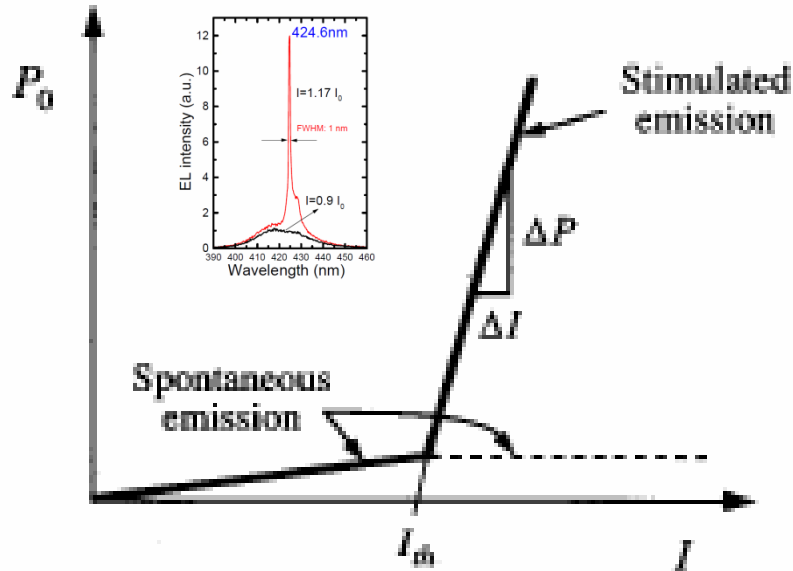
InGaN-based LD as an Example (ii)



GaN-based Violet/Blue LD



Laser Power – Differential Efficiency



(1) Internal quantum efficiency:

the efficiency of converting an electron-hole pair into a photon

(2) External differential efficiency

- related to internal quantum efficiency, η_i and the ratio of photons lost at mirrors and total loss

- α_a = internal loss = photons absorbed or scattered out of the cavity
- α_m = mirror loss = photons transmitted at facets = $(1/2L) \ln (1/R_1 R_2)$

• Measure

– external differential efficiency

$$P_0 = \eta_d \frac{h\nu}{q} (I - I_{th})$$

$$\eta_d = \frac{q}{h\nu} \frac{\Delta P}{\Delta I}$$

• Useful laser output is coupled out through the facets, and the rest is used to overcome the loss

$$\eta_d = \frac{\eta_i \alpha_m}{\alpha_i + \alpha_m}$$

Summary – Topic 14 (i)

- Lasing takes place when the internal gain, produced by stimulated recombination of injected carriers is stronger than the optical loss, and the allowed emission wavelengths are those that return in phase after a round trip of the optical cavity
- Semiconductor laser – a combination of optical cavity and electrically pumped gain section
- A laser may be formed by two partially reflective mirrors (cleaved facets of semiconductor) and is termed a Fabry Perot (FP) laser
- Operates by stimulated emission – photons in phase, emitted in the same direction
- Considering round trip losses of a laser we can derive the gain required to achieve a round trip with no loss/gain of optical power within the cavity

Summary – Topic 14 (ii)

- Threshold gain is the sum of “mirror loss” and “internal loss”
- Below threshold – LED, above threshold – the efficient conversion of carriers to photons
- Directional stimulated emission – laser “beam” which is readily focused – high launch power
- Above threshold – we can determine the output power or differential efficiency with regard to an electron to photon conversion efficiency and the ratio of mirror loss to total loss

Tutorial Questions

- T14.1 Draw and label a typical laser diode structure. Describe the requirements for lasing to take place in a semiconductor laser diode. What is meant by the terms “transparency current” and “threshold current” for a semiconductor laser diode?
- T14.2 What is meant by 'population inversion'? Explain the principles of stimulated optical emission and how it is related to optical absorption.
- T14.3 A Fabry-Perot laser of length L and optical confinement factor has active and passive region losses α_a and α_p and facet reflectivity R . Derive an expression for the threshold gain, g^{th} . Show that if one of the facets is silvered g^{th} is reduced by $-\ln(R)/2\Gamma L$ and if the passive region loss is eliminated it is further reduced by $\alpha_p(1-\Gamma)/\Gamma$.
- T14.4 Sketch the gain spectrum of a “bulk” laser diode as a function of current from zero applied current to lasing at room temperature. Mark on the schematic the threshold gain. Comment on the effect of raising the temperature.