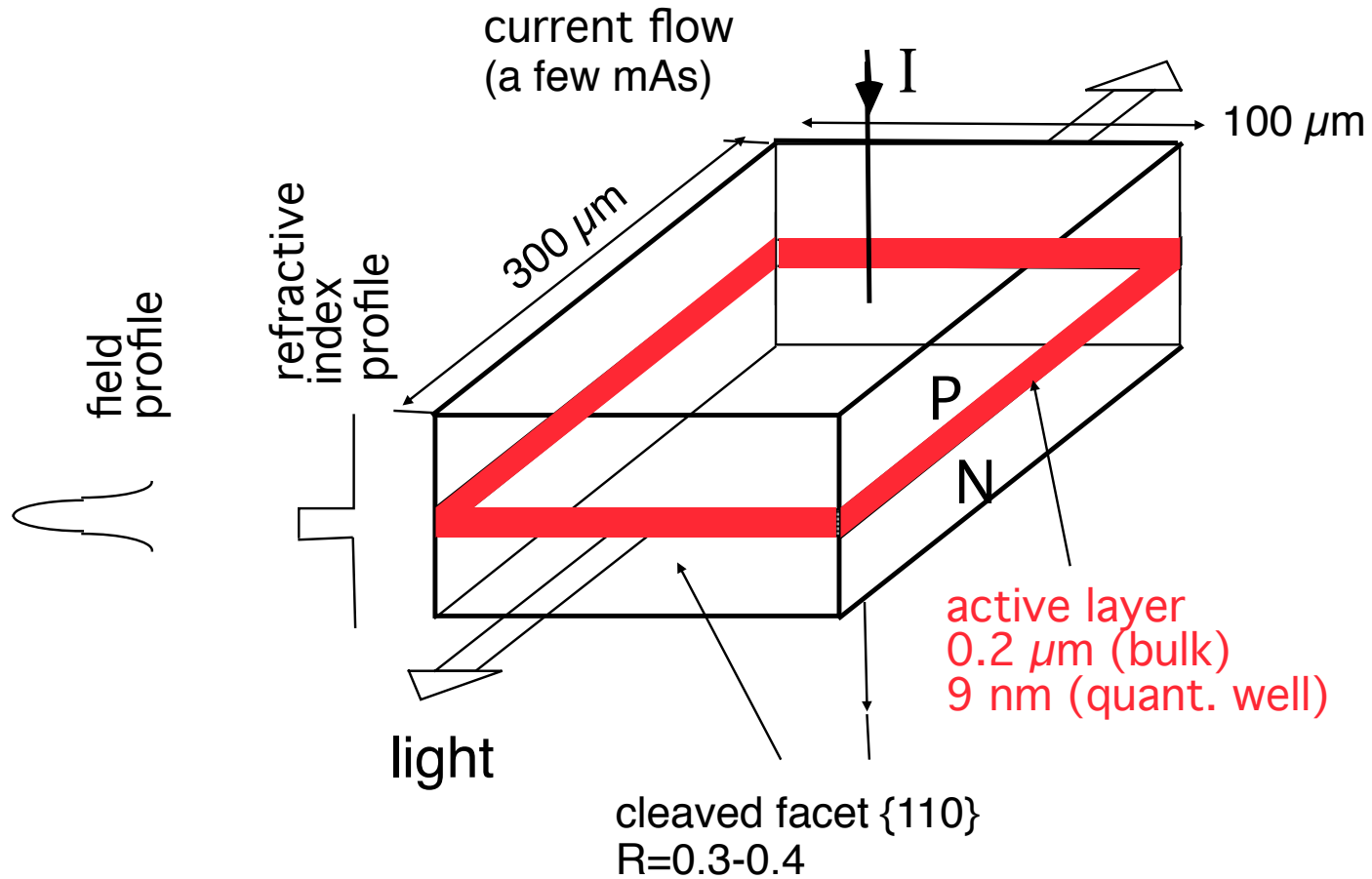


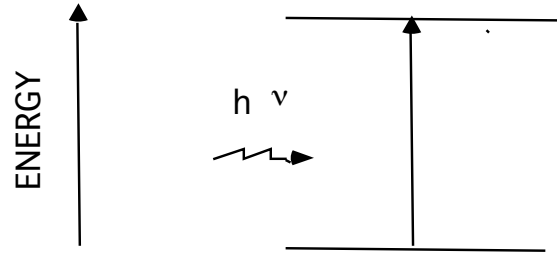
Semiconductor Lasers operating principle : outline

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- ▼ Distributed FeedBack lasers (DFB)
- ▼ Semiconductor Laser structures

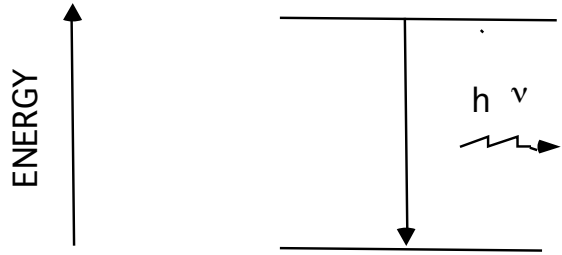
Double-heterojunction laser



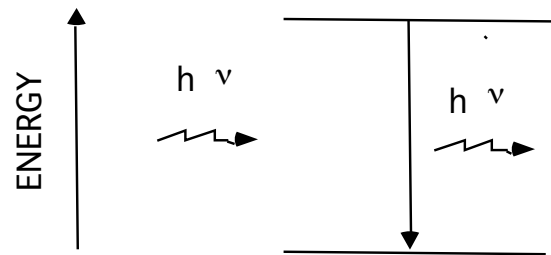
Optical transitions



Absorption

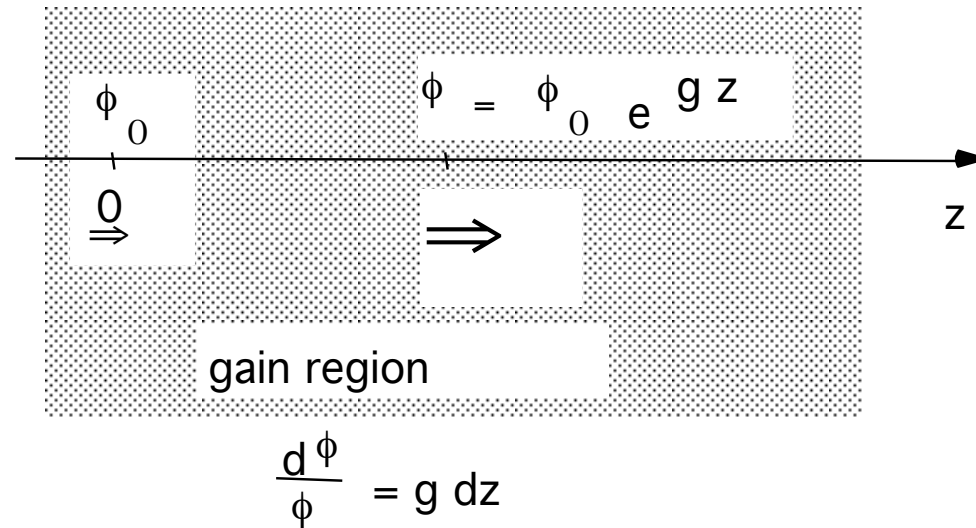


Spontaneous emission



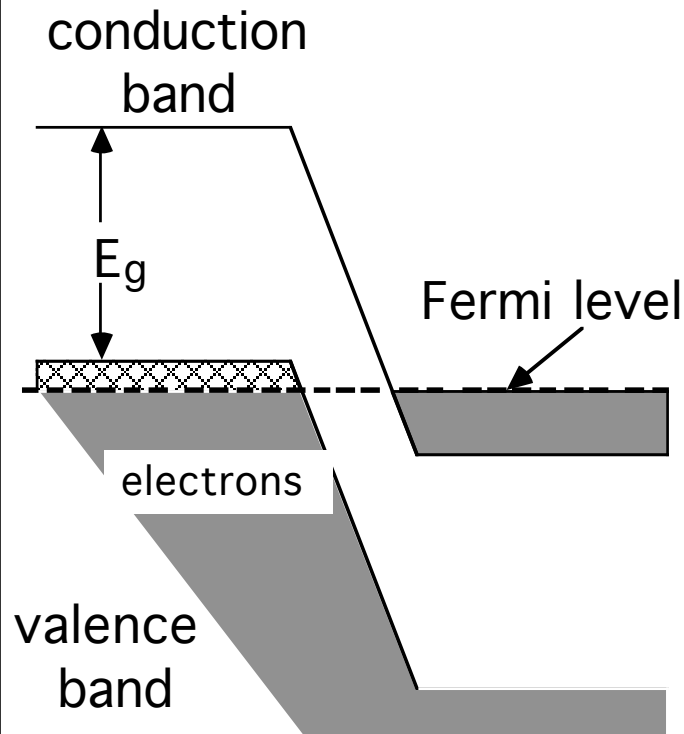
Stimulated emission

Optical gain

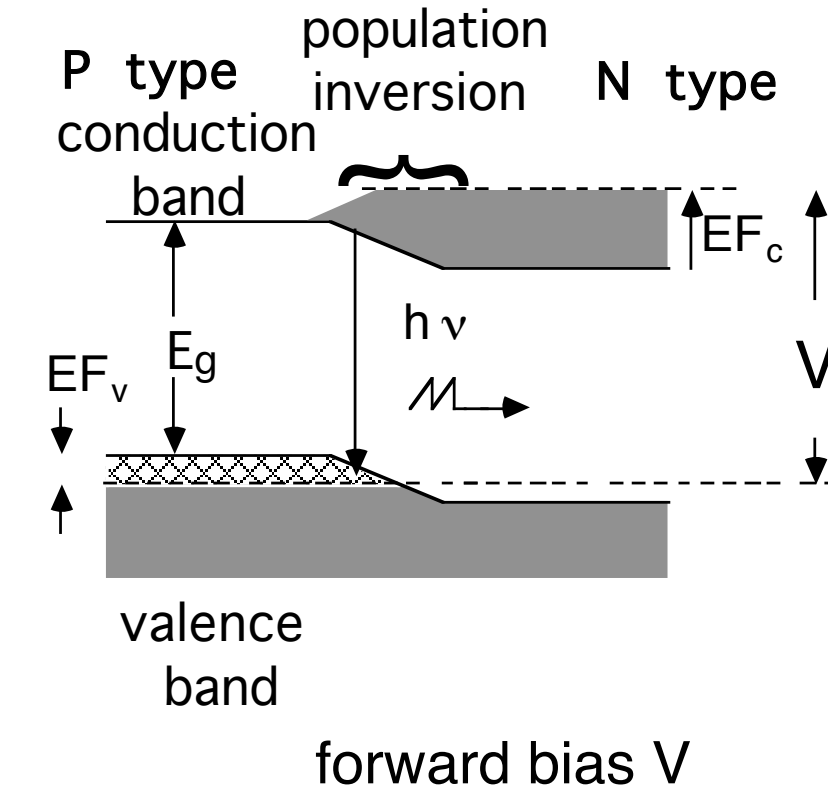


Φ (photons $s^{-1} cm^{-2}$) photon flux
 g (cm^{-1}) optical gain

Carrier confinement in a homo-junction laser, @ 0 K

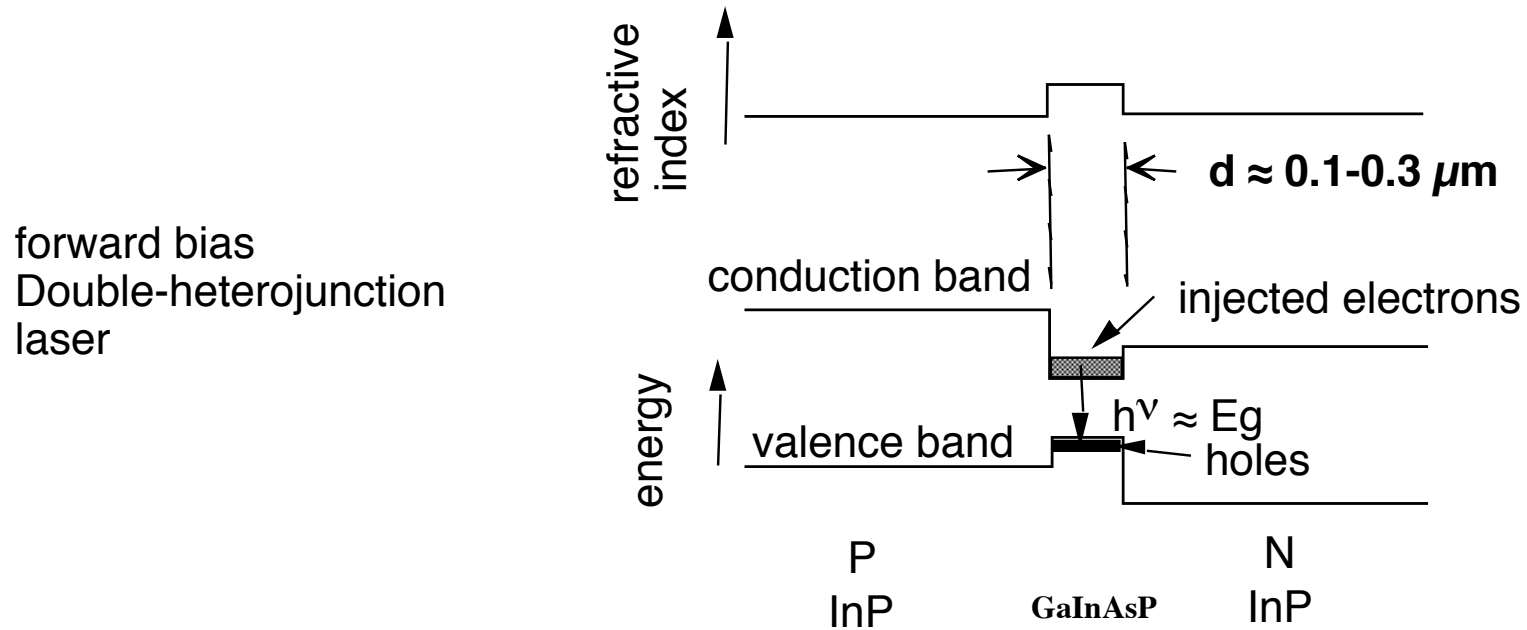


no bias, $V=0$



Carriers can diffuse and are poorly confined

Carrier and optical confinement in a double-heterojunction laser



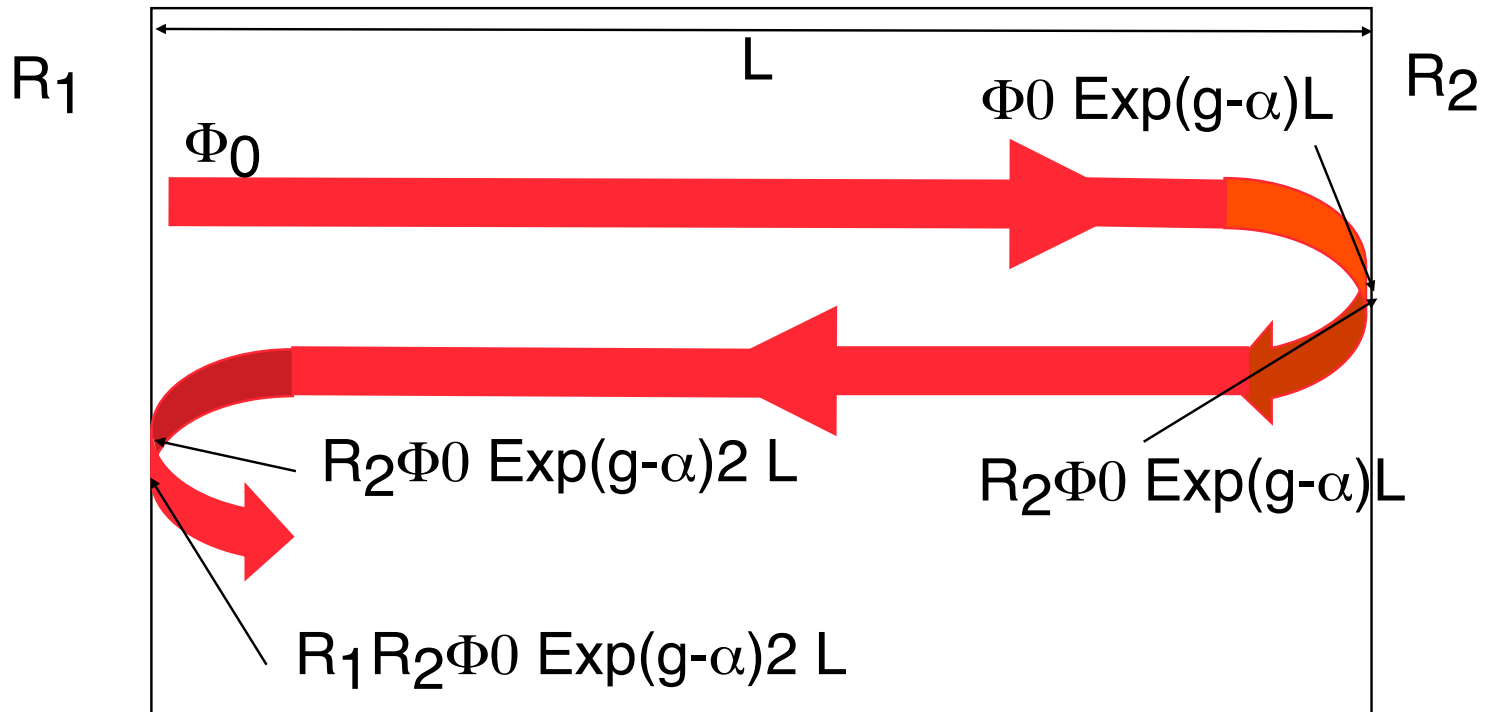
Condition for Net stimulated emission

$$E_g < h\nu < E_g + EF_c + EF_v$$

[I. Hayashi, M. B. Panish, F. K. Reinhart, « GaAs-Al_xGa_{1-x}As double-heterostructure injection lasers », J. App. Phys., vol. 42, pp 1929-1941, Apr. 1971]

[M.G. A. Bernard, G. Duraffourg, Phys. Status Solidi, 1, 699, 1961]

Threshold condition for a Fabry-Perot laser



gain

internal loss

mirror loss

$$\Phi_0 = R_1 R_2 \Phi_0 \text{Exp}(g-\alpha)2L$$

$$g = \alpha + (1/L) \text{Ln}(1/\text{Sqrt}(R_1 R_2))$$

Light-current characteristics

Linear gain approximation

$$g_{th} = a (N_{th} - N_t)$$

$$g_{th} = 100 \text{ cm}^{-1}$$

Optical confinement

$$\Gamma = 0.2$$

Case of a Double-Hetero structure laser

$$\Gamma g_{th} = \Gamma \alpha_{int} + (1 - \Gamma) \alpha_{cladd.} + 1/L \ln(1/R)$$

-> threshold carrier density $N_{th}(\text{cm}^{-3})$

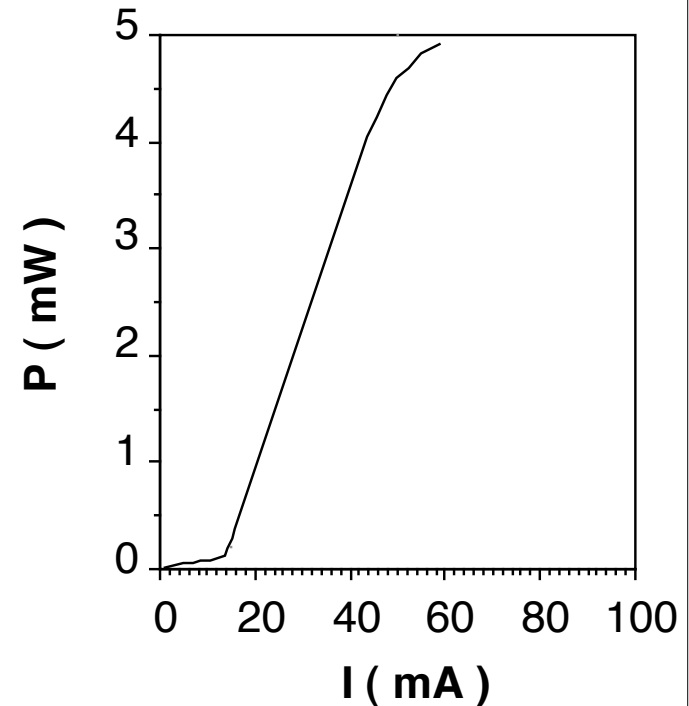
$$N_{th} = 2 \times 10^{18} \text{ cm}^{-3}$$

Recombination rate

$$J/ed = R_{rad}(N) + R_{non\ rad}(N)$$

-> threshold current density $J_{th}(\text{kA/cm}^2)$

$$J_{th} = 1 \text{ kA/cm}^2$$



$$J_{th}(\text{kA/cm}^2) = \frac{100 I_{th}(\text{mA})}{L(\mu\text{m}) w(\mu\text{m})}$$

Spontaneous and external differential efficiencies

Spontaneous radiative efficiency

$$\eta_{\text{spont}} = \frac{\text{radiat. recomb rate}}{\text{total recomb. rate}}$$

$$= \frac{(J_{\text{th}})_{\text{rad}}}{J_{\text{th}}}$$

$\eta_{\text{spont}} = 20 - 40 \%$

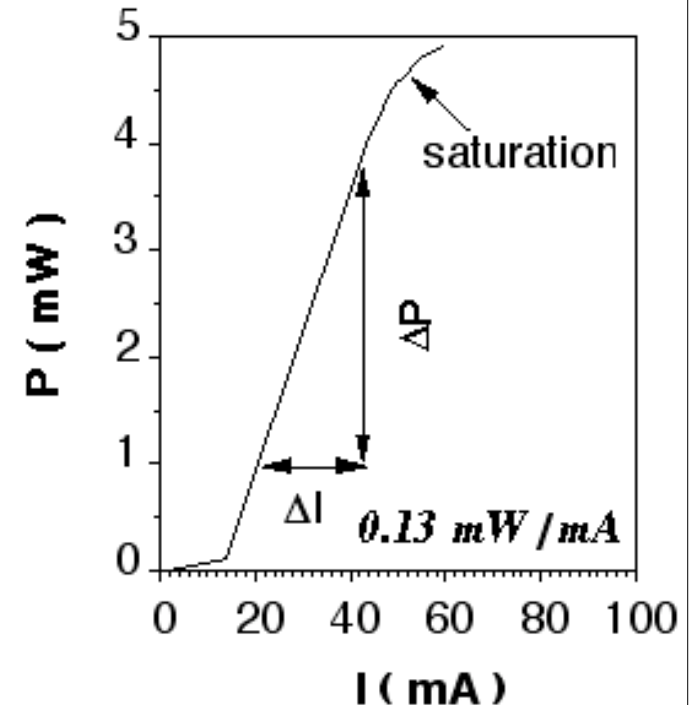
External differential efficiency
(per facet)

$$\eta_{\text{ext}} = \frac{\Delta_{\text{output photons}}}{\Delta_{\text{injected electrons}}} = \frac{\Delta P / h\nu}{\Delta I / e} = \frac{e}{h\nu} \frac{\Delta P}{\Delta I}$$

$$= \frac{\lambda(\mu\text{m})}{1.2398} \frac{\Delta P(\text{Watt})}{\Delta I(\text{A})}$$

$$= \frac{1}{2} \frac{\text{mirror loss}}{\text{total cavity loss}}$$

$\frac{\Delta P}{\Delta I} = 0.1 - 0.2 \text{ mW / mA}$
per facet



Optical spectrum for a Fabry-Perot laser

$$L = \frac{q \lambda}{2 n} \quad (1)$$

q integer
 λ free space wavelength
 L cavity length
 n effective index

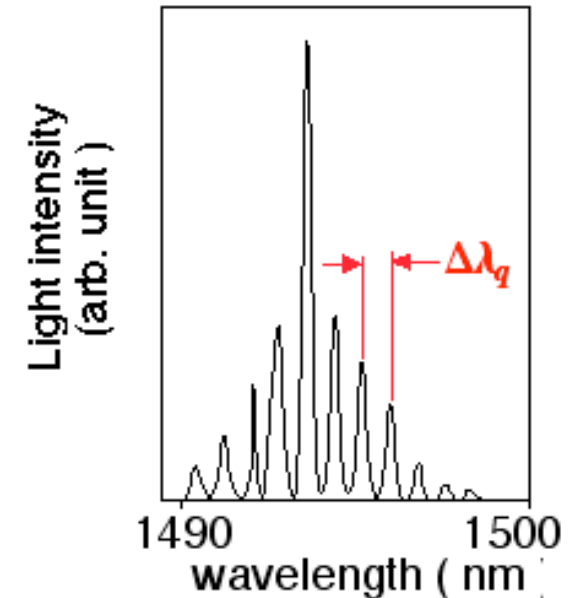
Longitudinal mode spacing $\Delta\lambda_q$
 by differentiation of (1)

$$0 = \frac{\lambda}{2 n} dq + \frac{q}{2 n} d\lambda - \frac{q \lambda}{2 n^2} dn \quad (2)$$

$$\Delta\lambda_q = \frac{\lambda^2}{2 L n_e} \quad (3)$$

$$n_e = n \left(1 - \frac{\lambda}{n} \frac{dn}{d\lambda} \right)$$

Effective group index



$$L = 400 \mu\text{m}$$

$$\lambda = 1494 \text{ nm}$$

$$n = 3.53$$

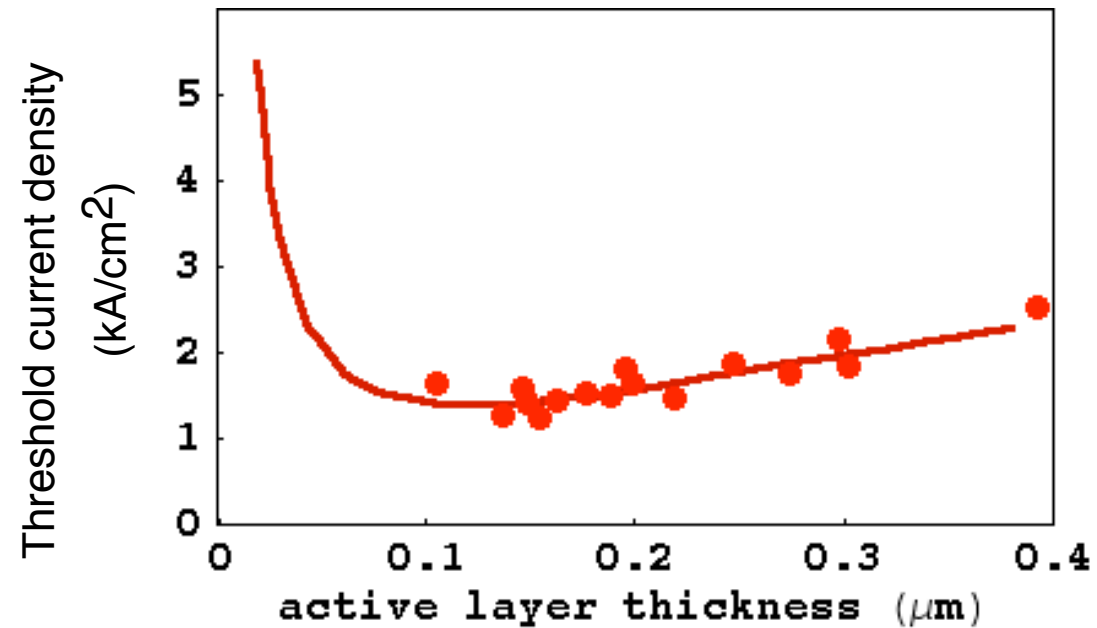
$$\frac{dn}{d\lambda} = -0.12 \mu\text{m}^{-1}$$

$$n_e = 3.70$$

$$\Delta\lambda_q = 0.75 \text{ nm}$$

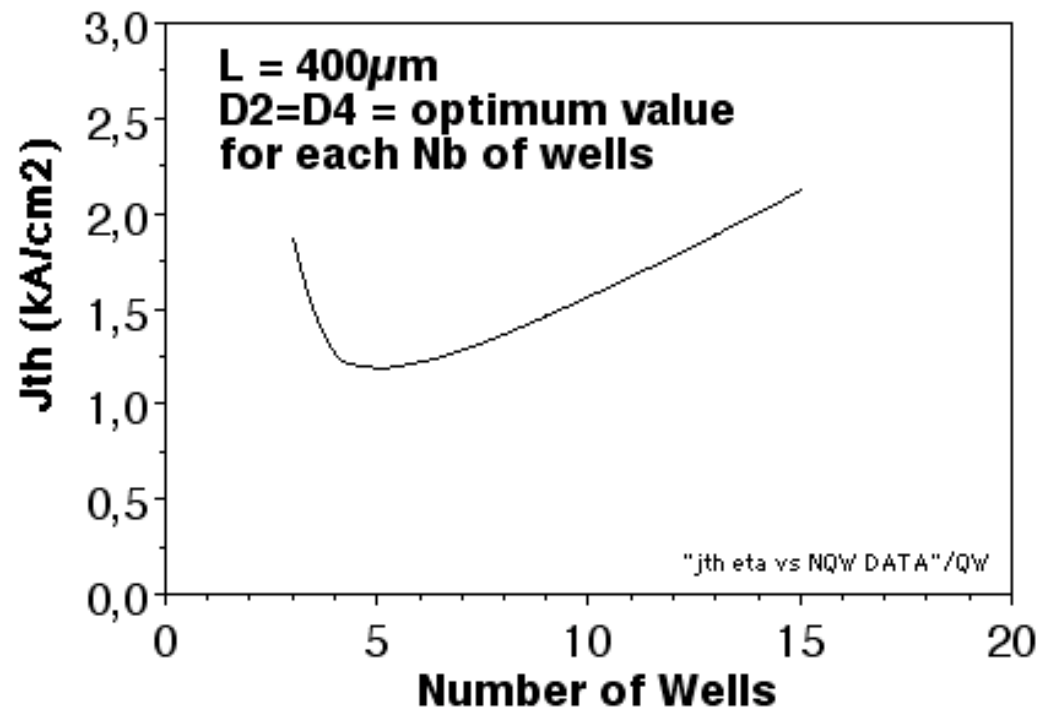
Threshold current density and active layer thickness

The threshold current density is minimum around 0.15 micrometer

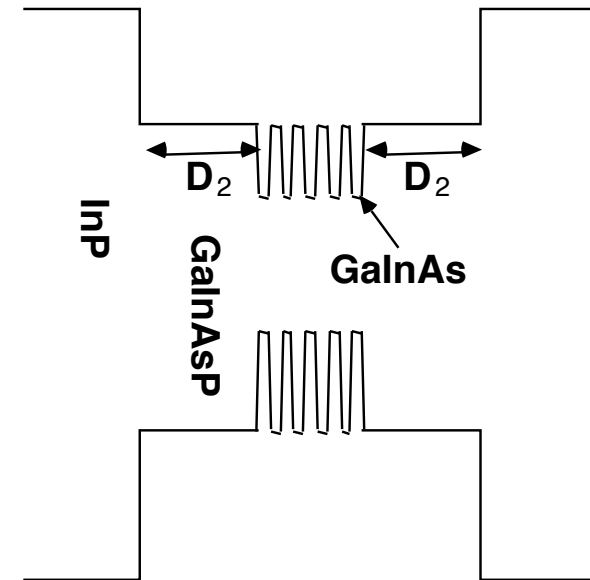
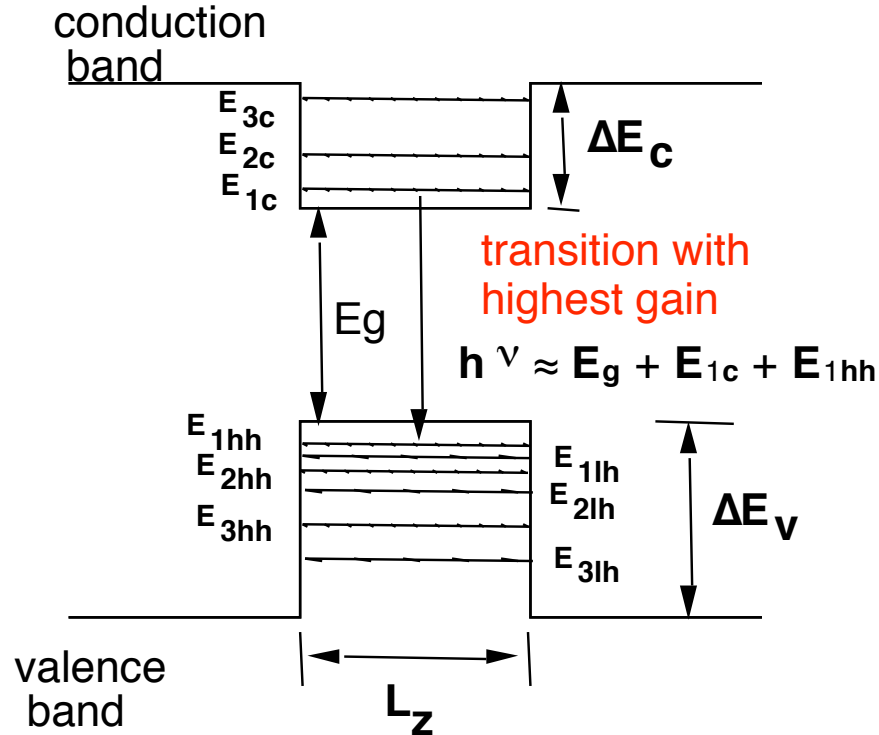


Threshold current density in a Quantum Well laser

The threshold current density is minimum for a 5-well laser



Quantum well semiconductor lasers

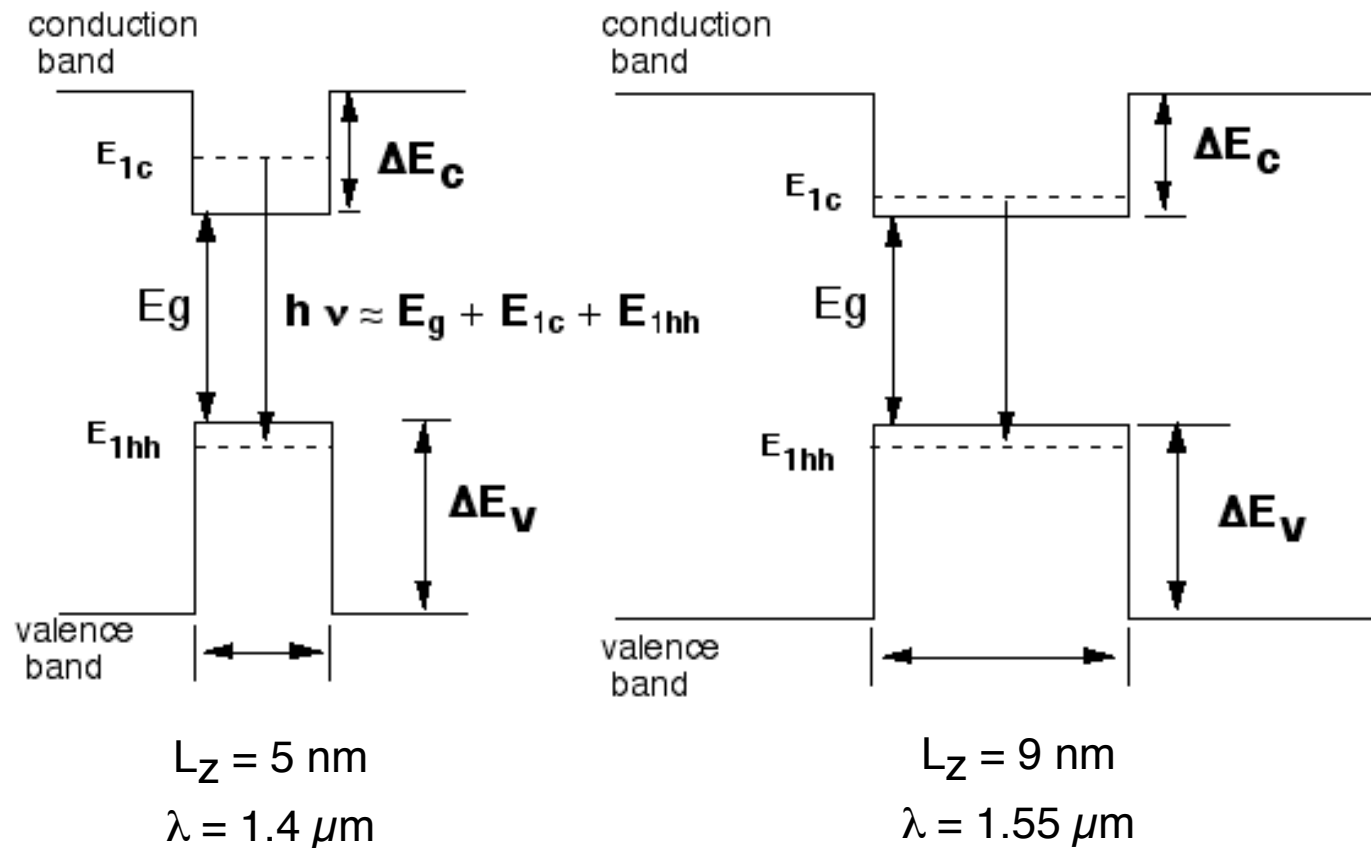


multiple quantum well laser

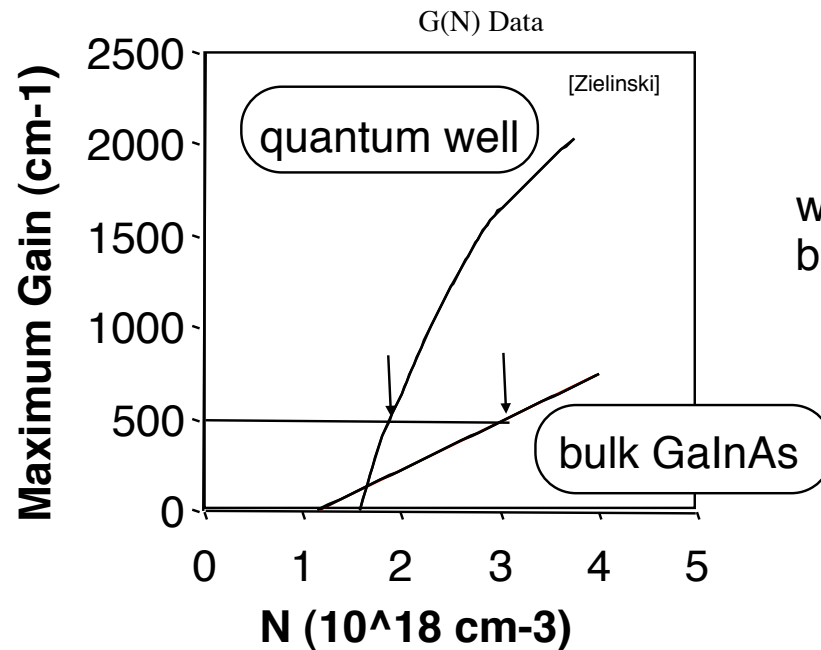
for an infinitely deep well
$$E_n = \frac{\hbar^2}{2m^*} \left(\frac{n\pi}{L_z} \right)^2$$

Control of the emission wavelength in a quantum well laser

- ▼ the energy $h\nu$ of the peak gain is determined by the width L_z of the well
- ▼ the emission wavelength is controlled by L_z



Maximum material gain in a quantum well laser

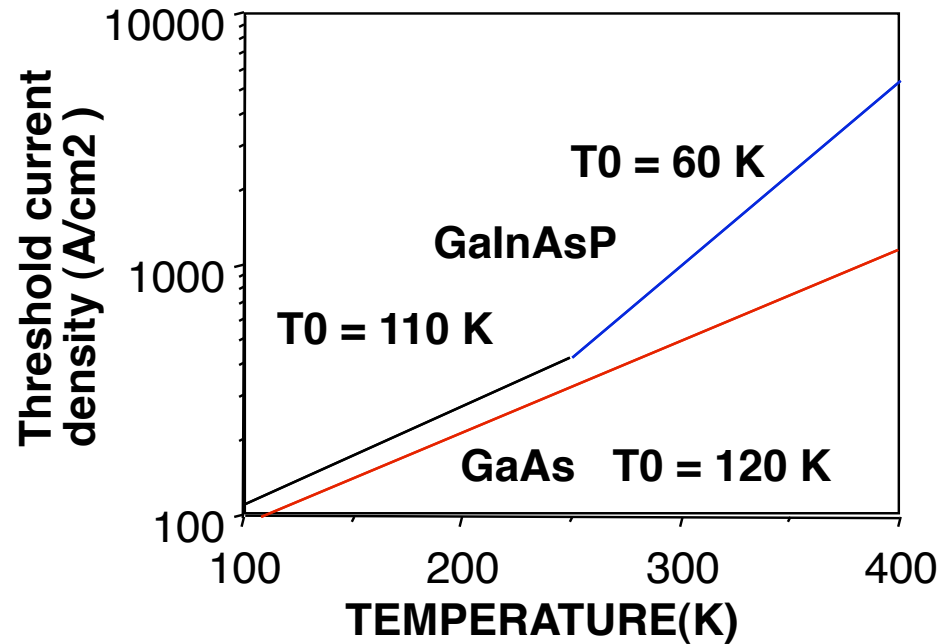


well: GaInAs
barrier: GaInAsP, $\lambda_g = 1.2 \mu\text{m}$

in quantum well lasers:

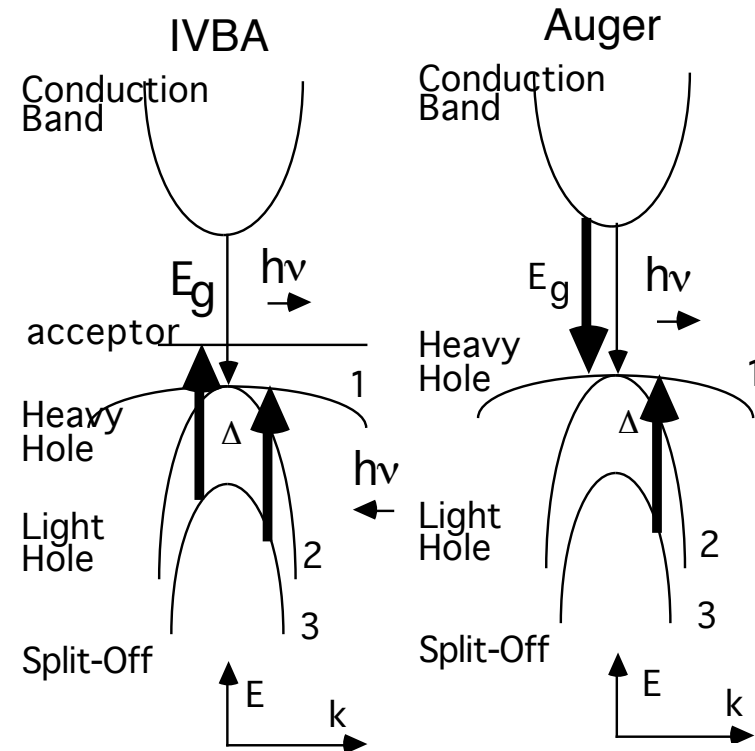
- threshold carrier density is lower
- higher modulation bandwidth (due to higher dg/dN)

Temperature dependence of the threshold current density



$$J_{th}(T) \approx J_0 e^{\frac{T}{T_0}}$$

low T₀ <-> high temperature sensitivity



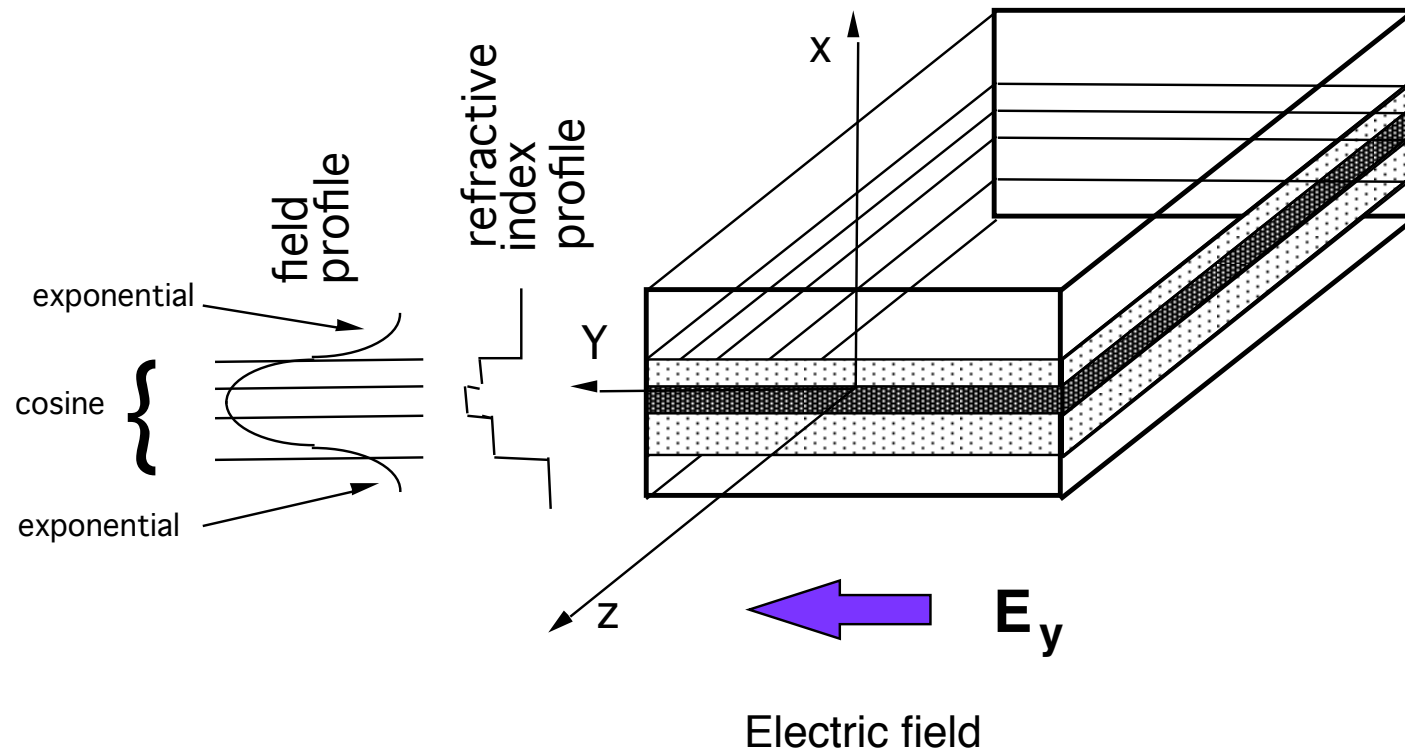
origin of the low T₀ in GaInAsP

- carrier leakage over barriers
- Inter Valence Band Absorption
- Auger recombination

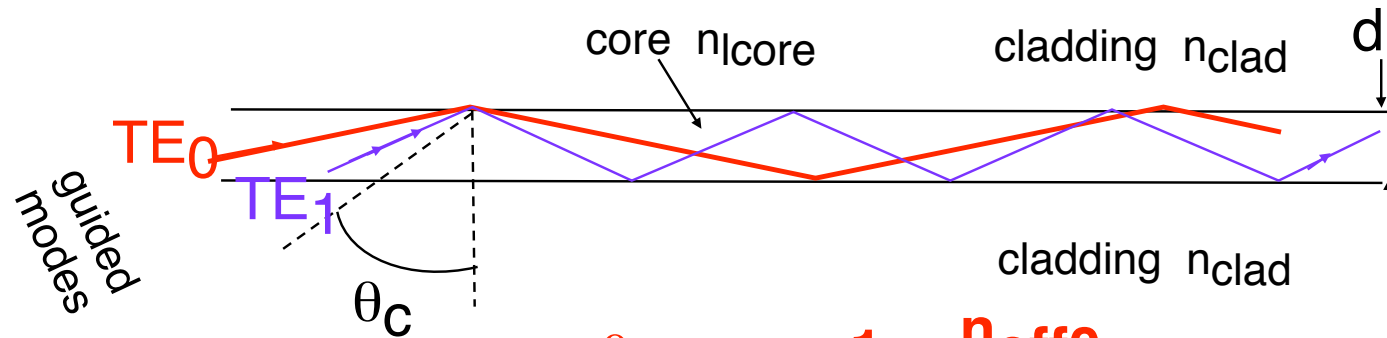
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Waveguide structure



Beam ray description of guided modes



$$\theta_c = \sin^{-1} \left(\frac{n_{\text{clad}}}{n_{\text{core}}} \right)$$

$$\theta_0 = \sin^{-1} \left(\frac{n_{\text{eff0}}}{n_{\text{core}}} \right)$$

$$\theta_1 = \sin^{-1} \left(\frac{n_{\text{eff1}}}{n_{\text{core}}} \right)$$

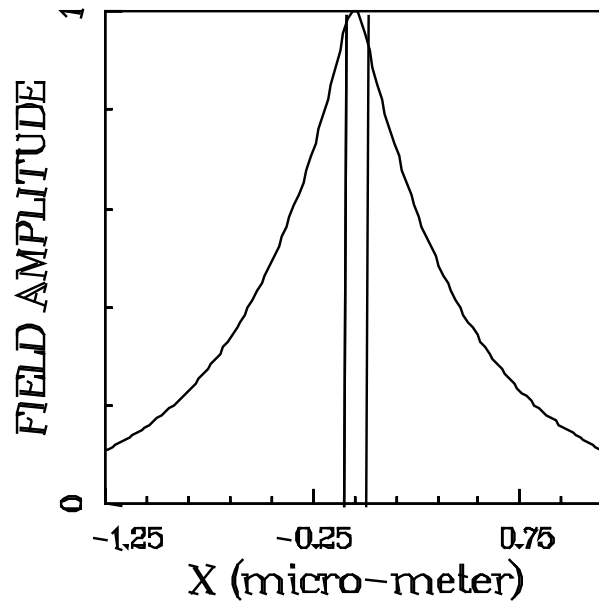
$n_{\text{core}} = 3.53$
 $n_{\text{clad}} = 3.17$
 $d = 0.75 \mu\text{m}$
 2 modes TE₀, TE₁

critical angle θ_c for total internal reflection

guided modes:
 $\theta > \theta_c$

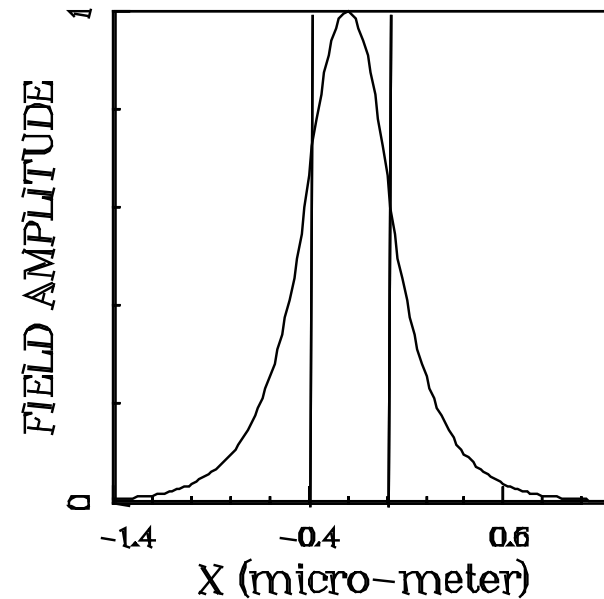
	θ (°)	n_{eff}
TE0	79	3.46
TE1	67	3.25
critical	64	3.17

Optical field profile (perpend. to junction plane)



$$n_{\text{core}} = 3.53$$

$$n_{\text{clad.}} = 3.17$$



$$d_{\text{act}} = 0.1 \mu\text{m}$$

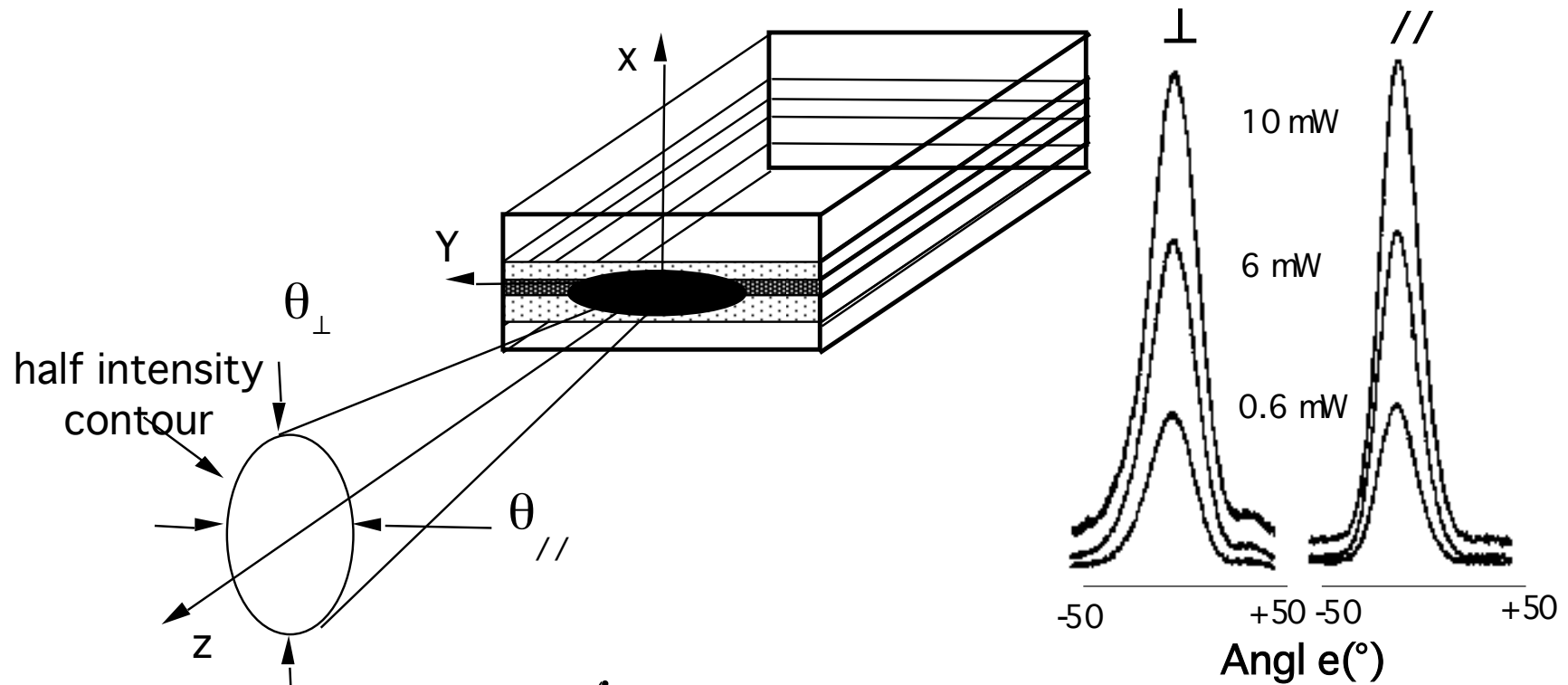
$$n_{\text{eff}} = 3.20$$

$$\Gamma = 0.17 \quad d_{\text{I/e2}} = 1.1 \mu\text{m}$$

$$d_{\text{act}} = 0.4 \mu\text{m}$$

$$n_{\text{eff}} = 3.38$$

$$\Gamma = 0.77 \quad d_{\text{I/e2}} = 0.65 \mu\text{m}$$



$$\mathbf{E}_{\perp}(\theta) = \int \mathbf{E}(\mathbf{x}) e^{-j[\mathbf{k} \sin \theta] \cdot \mathbf{x}} d\mathbf{x}$$

$$\theta_{//} = 23^{\circ}$$

$$\theta_{\perp} = 24^{\circ}$$

A. Accard, F. Brillouet, E. Duda, B. Fernier, G. Gelly, L. Goldstein, D. Leclerc, D. Lesterlin, J. Phys. III, France, Vol 2, p1727-1738, 1992

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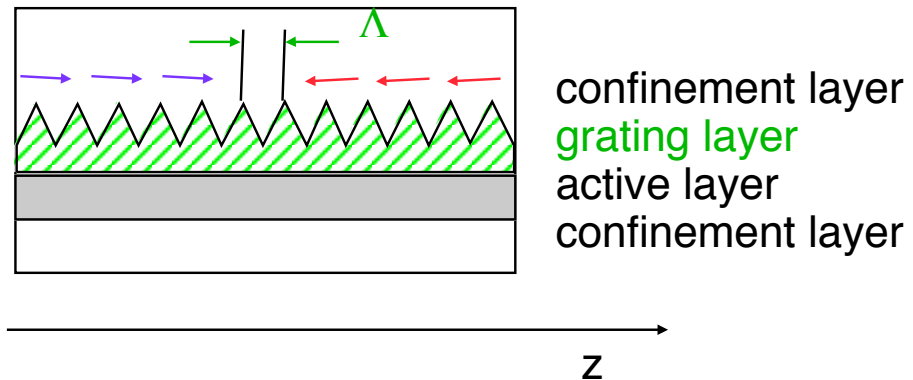
Principle of DFB lasers (Distributed FeedBack)

Optical feedback is achieved by a periodic perturbation along the propagation direction z (modulation of the effective index) with a grating

$\Lambda = \text{grating period}$

R **S**

case of index coupling:
the interaction between
waves **R** and **S** is described
by a real coupling coefficient
 $K(\text{cm}^{-1})$



optical feedback due to constructive interferences between
the two waves **R** and **S** travelling in opposite directions

Selective feedback for $\lambda \approx \lambda_{\text{Bragg}}$

$$[\Lambda + \Lambda \sin \theta] n_{\text{eff}} = q \lambda_{\text{Bragg}}$$

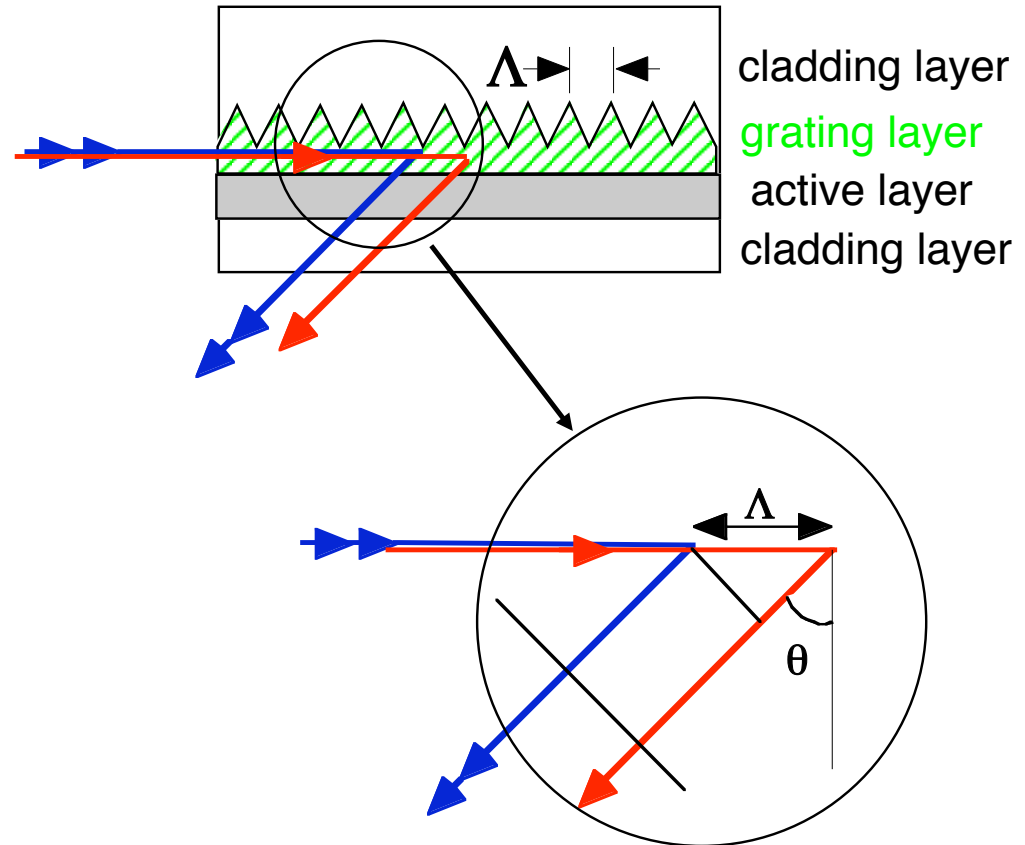
$$\theta = \pi/2 \quad \longrightarrow \quad \Lambda = \frac{\lambda_{\text{Bragg}}}{2 n_{\text{eff}}}$$

first order grating ($q=1$)

$$\lambda_{\text{Bragg}} \approx 1.5 \mu\text{m} \quad \Lambda \approx 0.2 \mu\text{m}$$

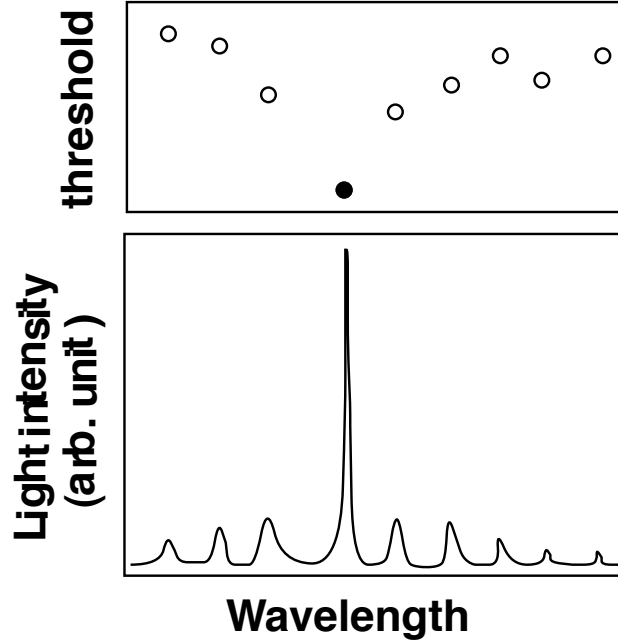
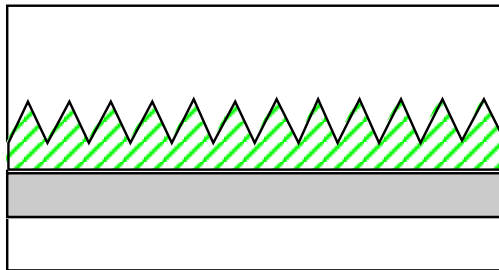
second order grating ($q=2$)

$$\lambda_{\text{Bragg}} \approx 1.5 \mu\text{m} \quad \Lambda \approx 0.4 \mu\text{m}$$

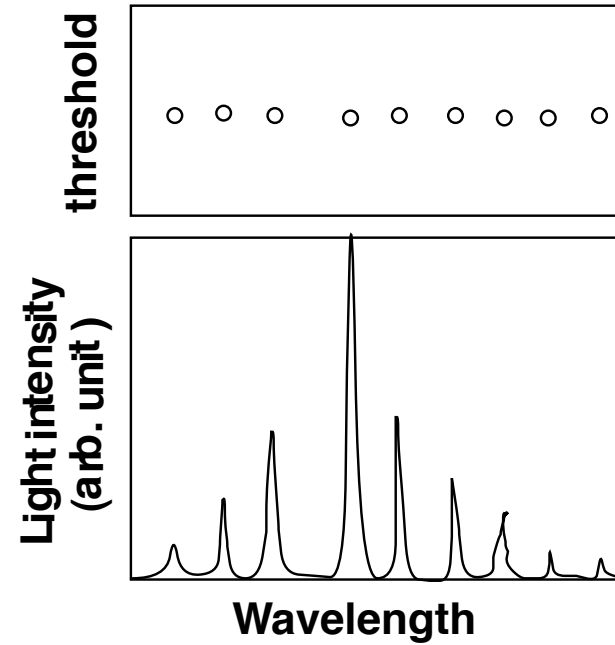
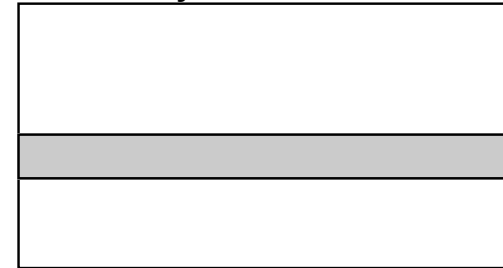


Modes and respective threshold

DFB laser



Fabry-Perot laser



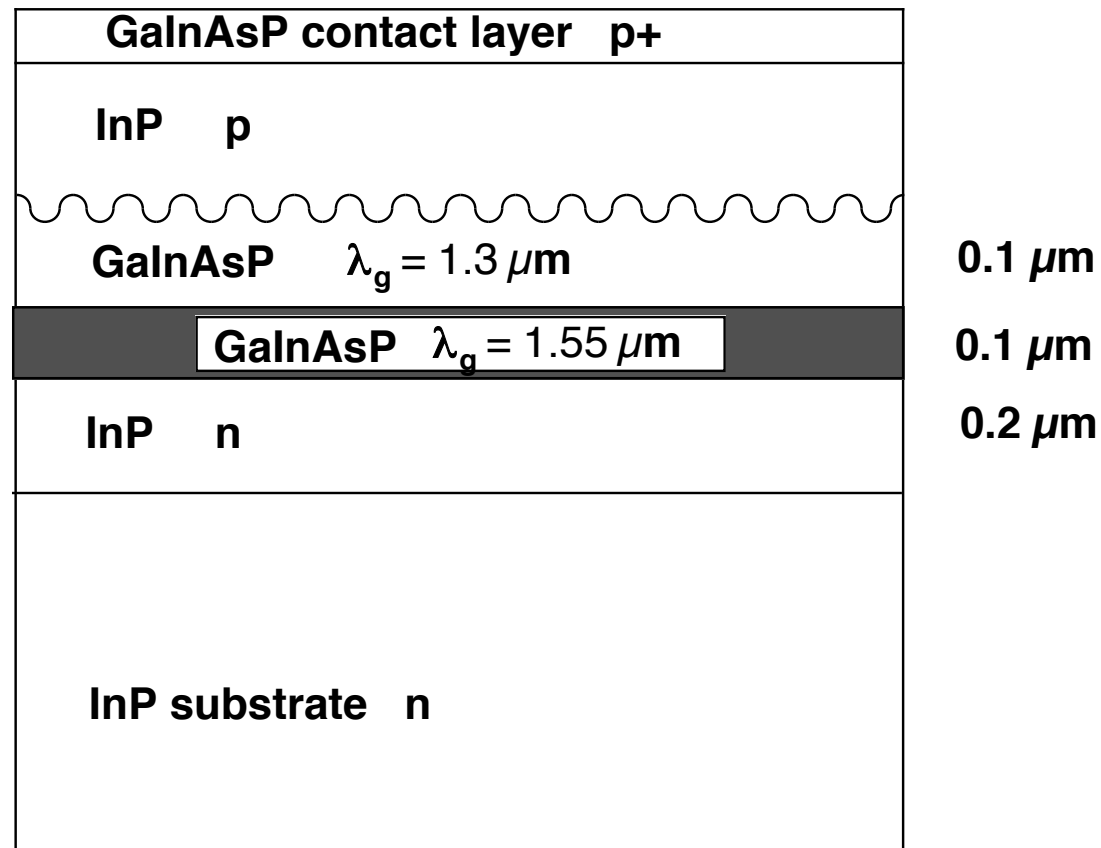
References (DFB lasers)

- [1] Kogelnik H., Shank C. V., " Coupled-wave theory of distributed-feedback lasers ", J. Appl. Phys.,1972, 43, pp 2327-2335
- [2] STREIFER, W., SCIFRES, D. R., BURNHAM, R. D., "Coupling coefficients for distributed feedback single-and double-heterostructure diode lasers ", IEEE J. Quantum Electron., 1975, QE-11, pp. 867-873
- [3] Kihara K., Soda H., Ishikawa H., Imai H. , "Evaluation of the coupling coefficient of a distributed feedback laser with residual facet reflectivity ", J. Appl. Phys.,1987, 62, pp 1526-1527
- [4] STREIFER, W., BURNHAM, R. D., SCIFRES, D. R. : "Effect of external reflectors on longitudinal modes of distributed feedback lasers", IEEE J. Quantum Electron., 1975, QE-11, pp. 154-161
- [5] Wang S., " Design considerations of the DBR injection laser and the waveguiding structure for integrated optics " ,IEEE J. Quantum Electron., 1977, QE-13, pp. 176-186
- [6] P. Brosson, C. Artigue, B. Fernier, D. Leclerc, J. Jacquet, J. Benoit, "A simple determination of the coupling coefficient in DFB waveguide structures", Electron. Letters, Vol. 24, pp 990, 1988.

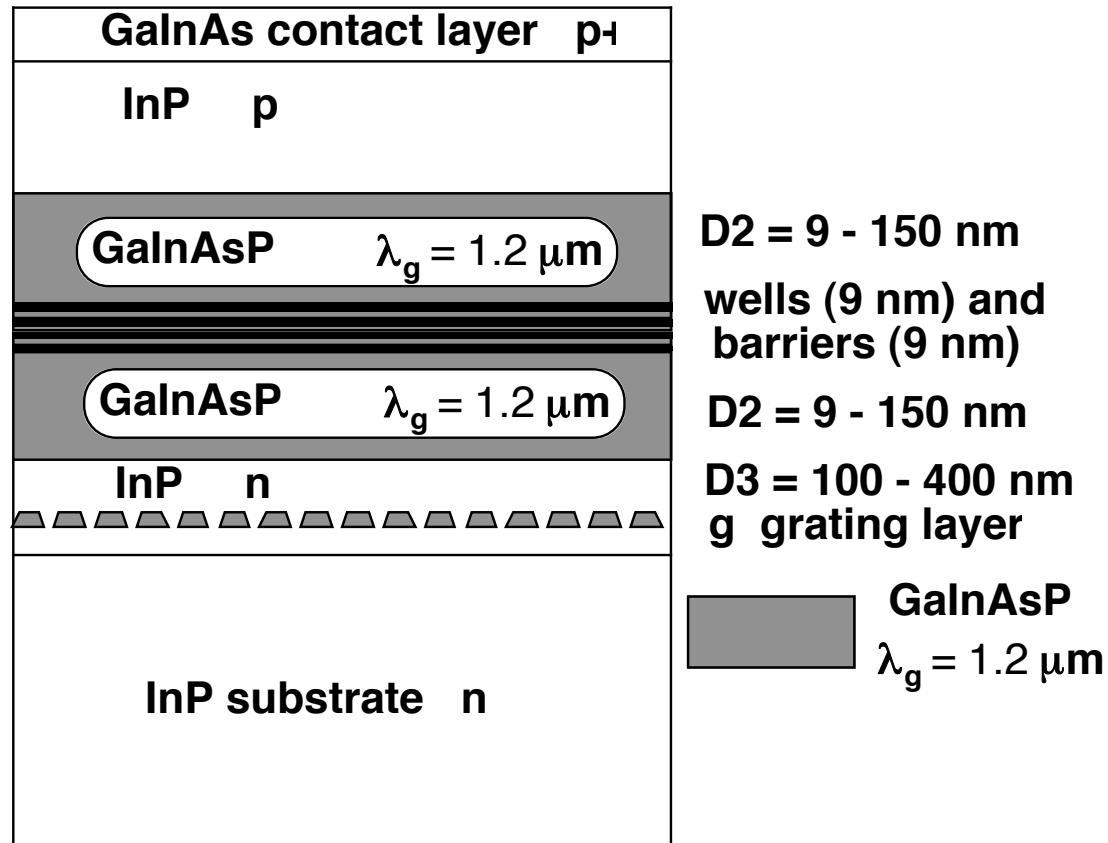
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Vertical laser structure (bulk active layer)



Vertical laser structure(Quantum Well)



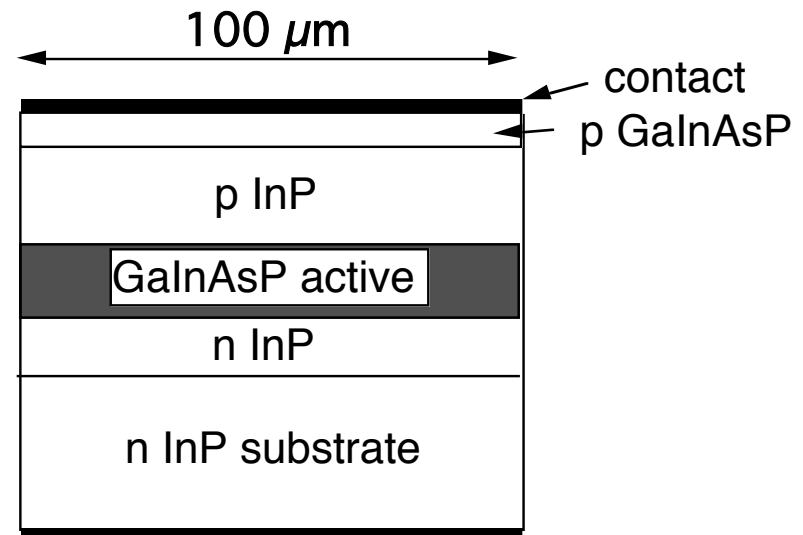
B. FERNIER, L. GOLDSTEIN, A. OLIVIER, A. PERALES, C. STARCK and J. BENOIT : " Multiquantum well lasers at $1.5\mu\text{m}$ by GSMBE ", 15th ECOC, SWEDEN, WeB 14 - 6, pp. 264 - 267, (1989)

Broad area lasers

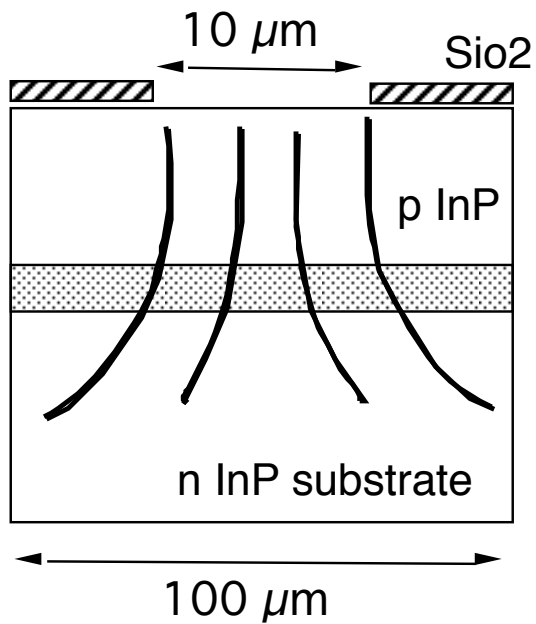
Simple laser structure to test the lasers

- no lateral current spreading
- good determination of
 - $J_{\text{threshold}}$ (kA/cm²)
 - external efficiency

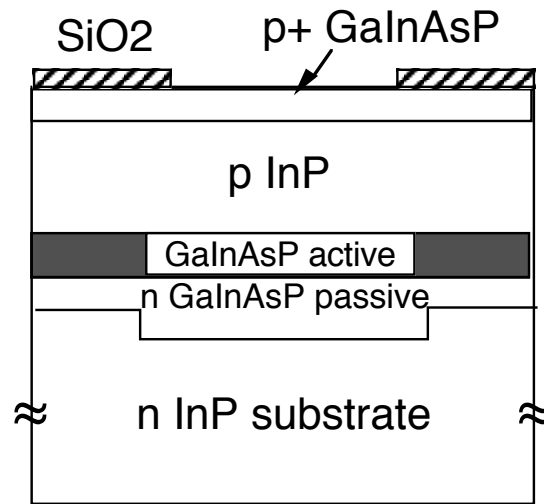
requires pulsed operation to avoid heating
(high $I_{\text{threshold}} = 0.5\text{-}3\text{ A}$)



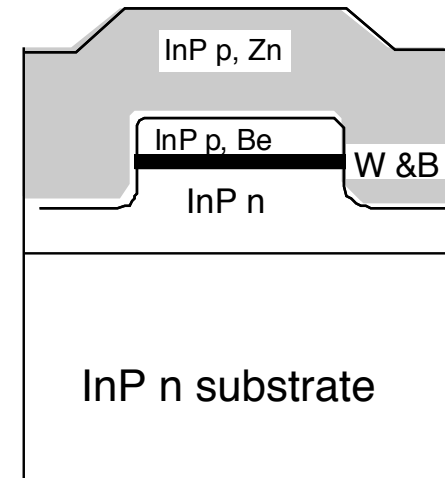
Stripe lasers



Gain guided
(light is absorbed in the unpumped region)



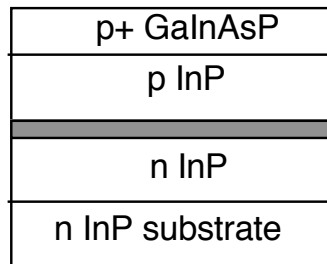
$\Delta n = 0.001 - 0.01$



$\Delta n = 0.1 - 0.3$

Index guided

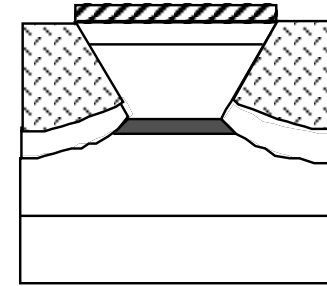
Buried double-hetero-structure laser processing(1)



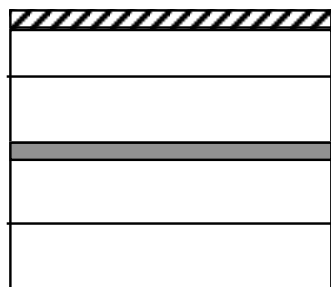
1 epitaxy



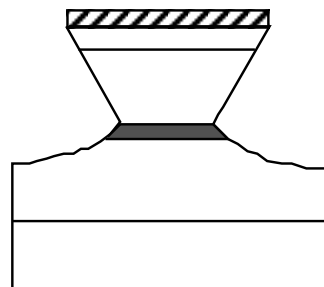
3 SiO2 engraving



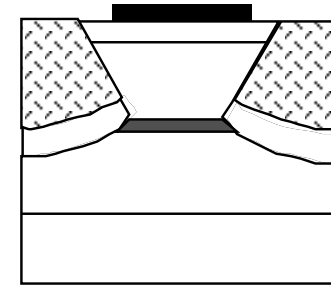
5 epitaxial regrowth



2 SiO2 deposition

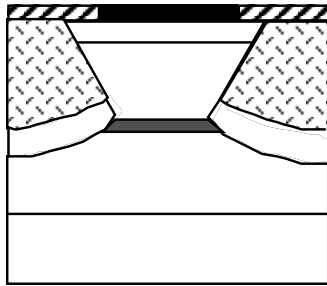


4 mesa engraving

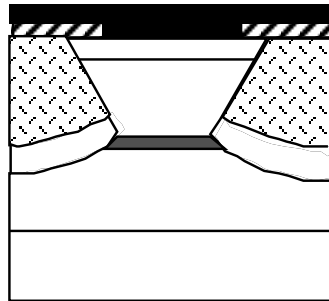


6 AuZn contact & engraving

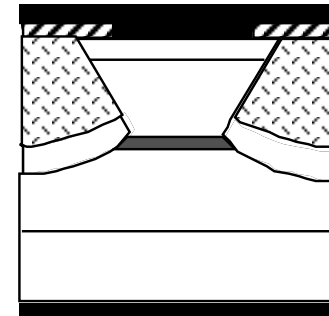
Buried double-hetero-structure laser processing(2)



7 SiO₂ deposition



8 TiPtAu p contact



9
 • lapping & chemical polishing
 • AuGeNi n contact

