Semiconductor Lasers for Optical Communication

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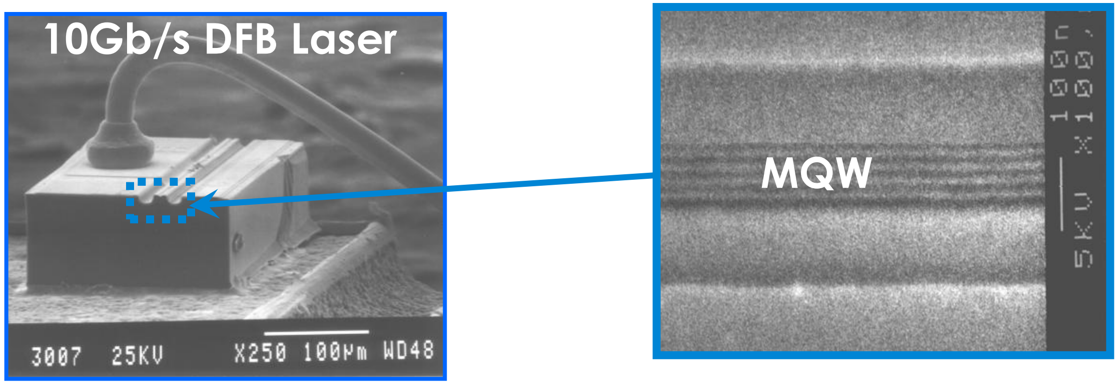


AVAGO
TECHNOLOGIES

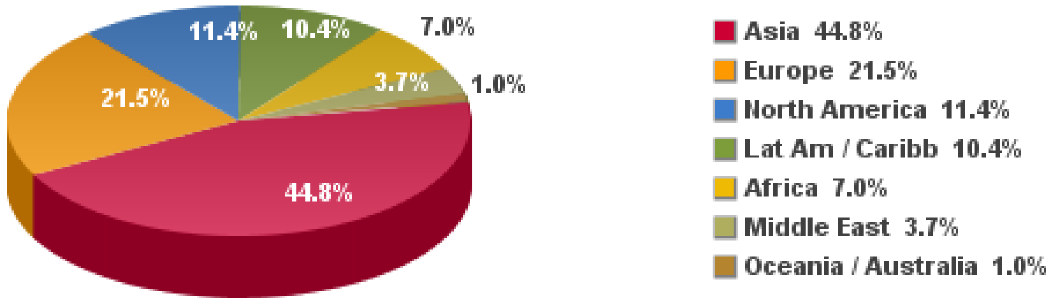
Outline

1) Background and Motivation
    - Communication Traffic Growth
    - Why Photonics?
    - Photonics evolution
2) Semiconductor Laser Basics
    - Active material
    - Optical Feedback

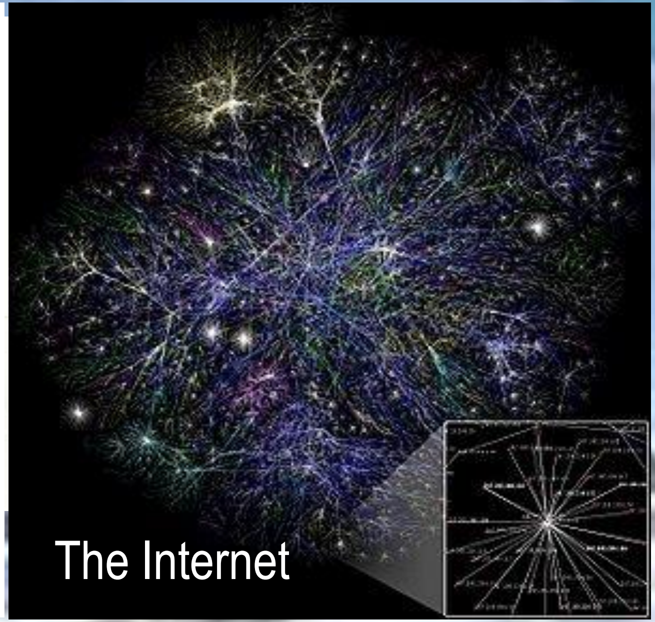
Communication Growth

Communication has always been one of the main driving force for the development of new technologies:
Telegraph, Telephone, Fiber Optic, Laser, …

Internet Users in the World
Distribution by World Regions - 2012 Q2



Source: Internet World Stats - www.internetworldstats.com/stats.htm
Basis: 2,405,518,376 Internet users on June 30, 2012 (34.3% world population)
Copyright © 2012, Miniwatts Marketing Group


The Internet

Worldwide communication traffic is doubling every 18 months (2dB/year)

Traffic structure and Energy Consumption

- Data Centers and the Internet consume about 4% of electricity (8.7 $\times$ 10^{11} kWhr/year including PCs)
- By 2018 the energy utilized by IP traffic will exceed 10% of the total electrical power generation in developed countries (1)
- Most of the traffic is between machines and much of the information created today cannot even be stored (2)

- 100 MW power
- Tens of thousands of fibers

From Donn Lee (Facebook)

1 Server = 1 SUV

FACEBOOK (3) :

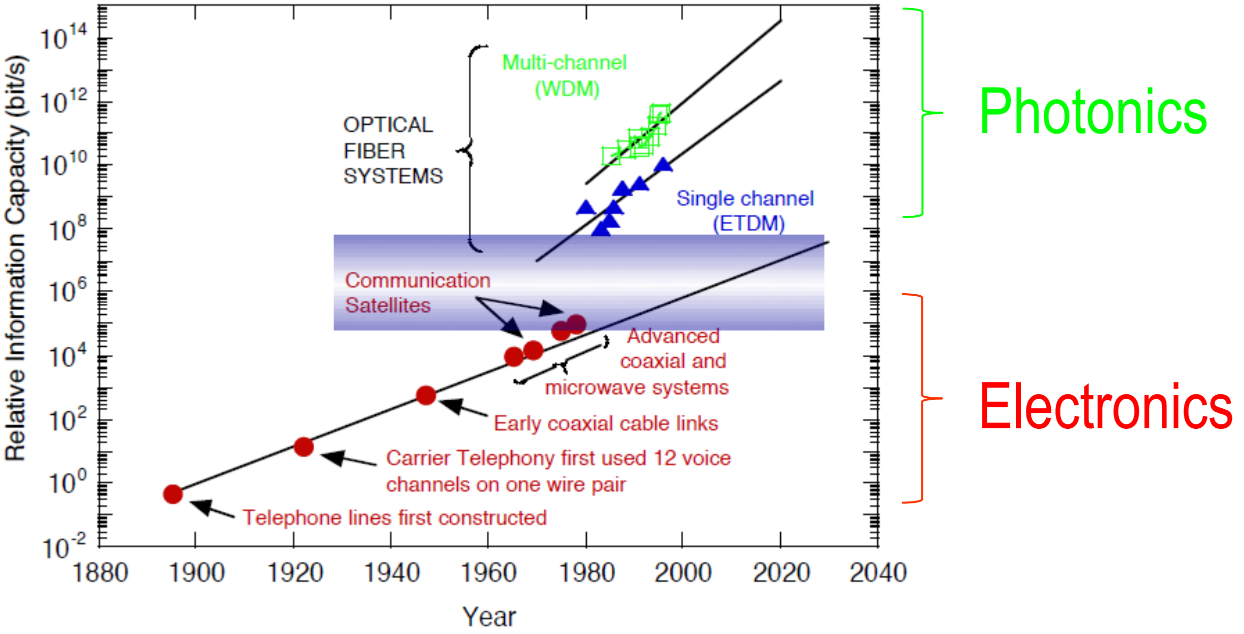
- 1.01 billion active users worldwide (23M in Italy, 39.5% population)
- 584 million active users every day
- 10.5 billion minute/day

(1) L.Kimerling, MIT
(2) R.Tkatch, Alcatel Lucent
(3) D. Lee, Facebook
} *European Conference on Optical Communication 2010*

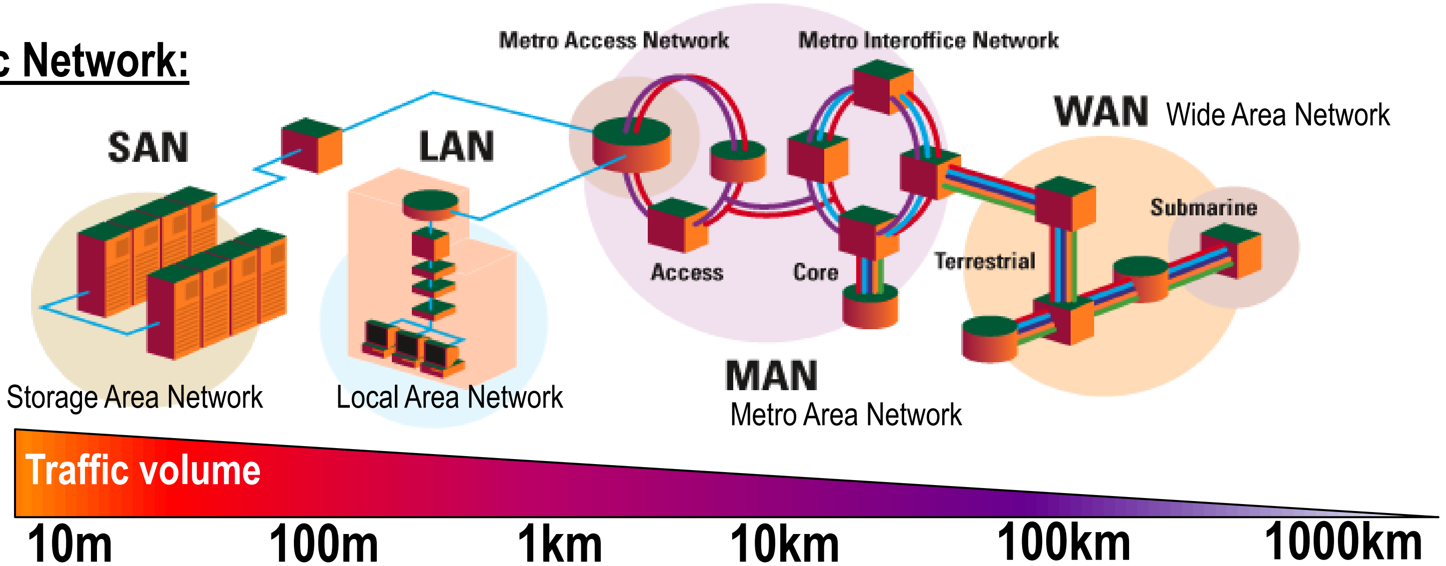
Why Photonics?

- Short monochromatic optical pulses are easily produced with semiconductor lasers **(ps range ⇒ Gb/s to Tb/s)**
- Photons do not interact each other
- Photons can be propagated in optical fiber with very low loss **(0.2dB/km)**
- Several data streams at different wavelength can be combined, propagated together in optical fibers and then split **(high channel capacity)**

Photonics in Optical Communication



Today Photonic Network:



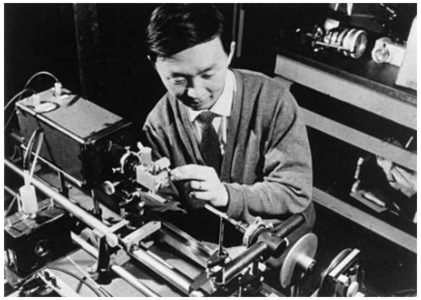
Photonics

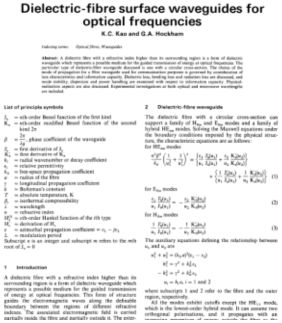
Photonics:
Science and technology of light

- Emission,
- Transmission,
- Processing (modulation, switching, amplification, …)
- Detection

Began with **Laser** (1960) and **Fiber Optic** (1966) inventions.
These inventions formed the basis for the telecommunications revolution of the late 20th century and provided the infrastructure for the internet.

1st Laser demonstration : T. Maiman 1960





Dielectric-fibre surface waveguides for optical frequencies
K.C. Kao and G.A. Hockham

1st Low-Loss Fiber Optic Proposal: C. Kao 1966

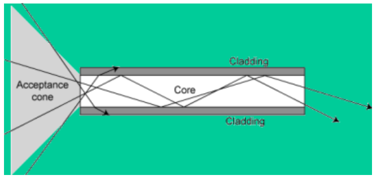
Fiber Optics

1966: First proposal of fiber optic for telecom. Basic design [Kao STC, Nobel Prize 2009]

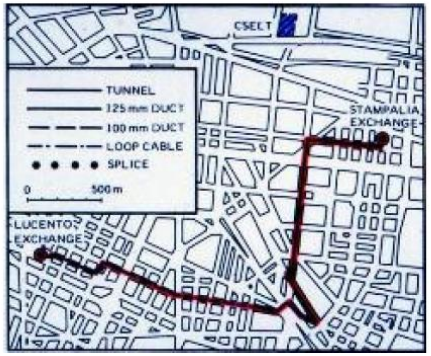
1970: Production of first fiber optic [Corning]

1976-77: First fiber optic networks

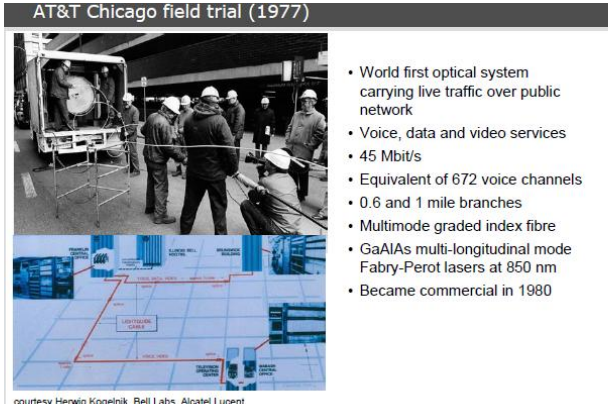
1988: First transoceanic fiber-optic cable (3148 miles, 40000 simultaeous telephone calls)



C. K. Kao receiving his Nobel Prize Stockholm 2009



First operative optical cable in urban areas **Torino 1976**

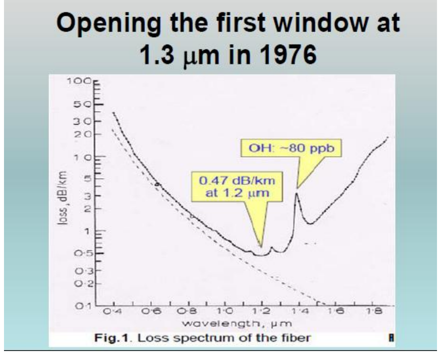


AT&T Chicago field trial (1977)

- World first optical system carrying live traffic over public network
- Voice, data and video services
- 45 Mbit/s
- Equivalent of 672 voice channels
- 0.6 and 1 mile branches
- Multimode graded index fibre
- GaAlAs multi-longitudinal mode Fabry-Perot lasers at 850 nm
- Became commercial in 1980

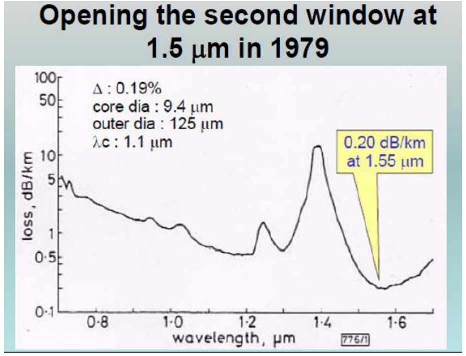
courtesy Herwig Kogelnik, Bell Labs, Alcatel Lucent

First optical system carrying live traffic over public network **Chicago 1977**



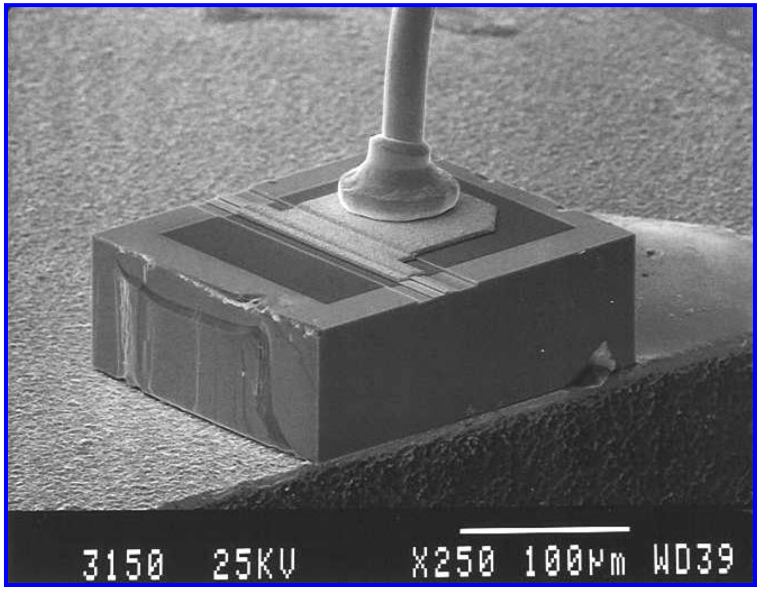
Opening the first window at 1.3 μm in 1976

Fig.1. Loss spectrum of the fiber



Opening the second window at 1.5 μm in 1979

Semiconductor Laser Basics



Semiconductor LASER history

1962: First Realization of Semiconductor Laser (GaAs @T = - 200 °C) [GEC, IBM, MIT]

1963: Proposal of Heterostructure Semiconductor Laser (H. Kroemer, Z. Alferov: Nobel Prize 2000)

1970: First Realization of Heterostructure Semiconductor Laser (Z. Alferov)

1972: Proposal of Distributed Feedback Laser (DFB)

1970: Room Temperature CW operation of 1.5μm Laser

1977: Proposal of Vertical Cavity Surface Emitting Laser (VCSEL)

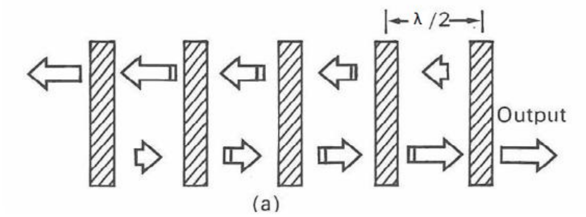
1984: First Realization of Strained MQW in semiconductor laser

1988: First Realization of VCSEL

2000: First Uncooled Telecom Lasers

Theory of Distributed Feedback (DFB) Lasers

H. Kogelnik and C. V. Shank 1972

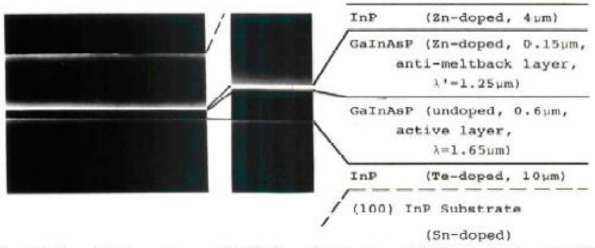


Two Modes Operation (for Refractive Index Coupling)

Z. Alferov receiving his Nobel Prize Stockholm 2000

RT-CW Operation of 1.5μm Laser

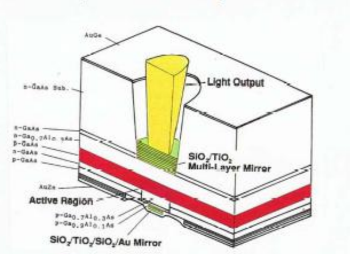
~ GaInAsP/InP Laser ~



- S. Arai, Y. Itaya, Y. Suematsu,and K. Kishino, 11th Conf. on Solid State Devices (SSDM), Tokyo 3-4 (Aug. 1979). S. Arai, M. Asada, Y. Suematsu, and Y. Itaya, *Jpn. J. Appl. Phys.*, vol. 18, no. pp. 2333-2334, Dec. 1979,

Idea by Kenichi Iga, 1977

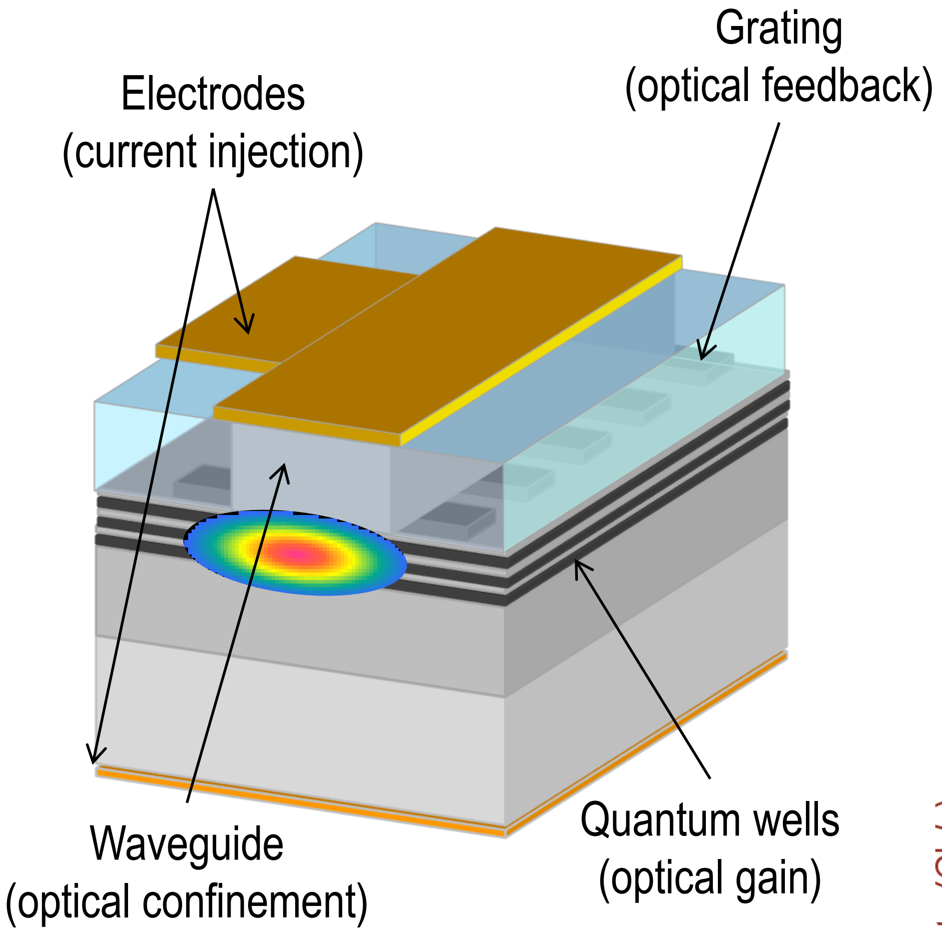
RT-CW, Achieved in August 1988



1988

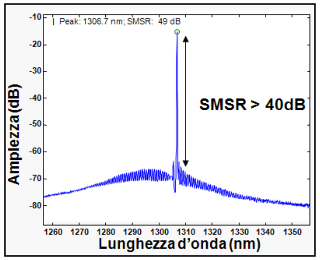
K. Iga, F. Koyama, and S. Kinoshita, IEEE J. Quant. Electron. 24, 1845(1988).
F. Koyama, and S. Kinoshita, and K. Iga, Appl. Phys. Lett. 55, 221, (1989).

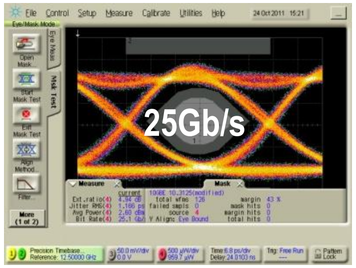
Laser requirements for optical communication



DFB MQW Laser

- **High bandwidth (≥ 10Gb/s)**
- **Single mode operation**
- **Low consumption**
- **Uncooled operation (up to 80°C)**

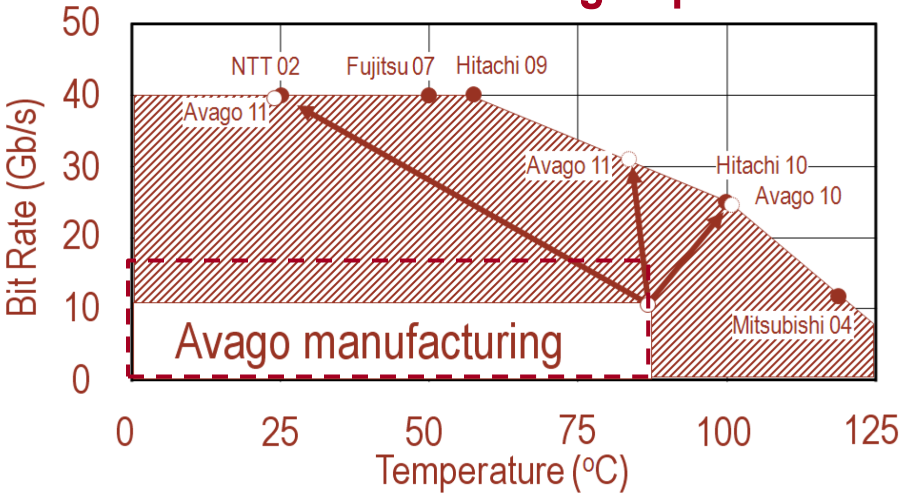




```
                current       10GBE 10.3125(modified)
Ext.ratio(4)    4.94 dB        total wfms  126            margin  43 %
Jitter RMS(4)   1.166 ps     failed smpls  0           mask hits  0
Avg Power(4)    2.60 dBm           source  4         margin hits  0
Bit Rate(4)     25.1 Gb/     Y Align: Eye Bound       total hits  0
```

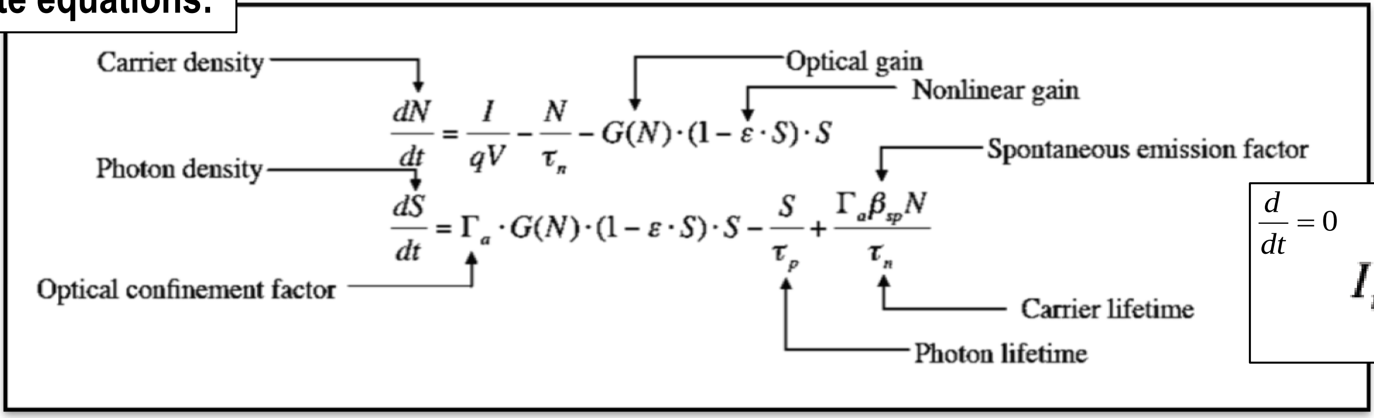
```
Precision Timebase...  Reference: 12.50000 GHz
3  50.0 mV/div  0.0 V
4  500 µW/div  959.7 µW
Time 6.8 ps/div  Delay 24.0103 ns
Trig: Free Run
```

State of Art of uncooled high-speed lasers



High-speed laser key factors

Laser rate equations:



$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_n} - G(N)\cdot(1-\varepsilon\cdot S)\cdot S$$

$$\frac{dS}{dt} = \Gamma_a \cdot G(N)\cdot(1-\varepsilon\cdot S)\cdot S - \frac{S}{\tau_p} + \frac{\Gamma_a \beta_{sp} N}{\tau_n}$$

$$\frac{d}{dt} = 0$$

$$I_{th} = \frac{qVN_{th}}{\tau_n}$$

1 2 3

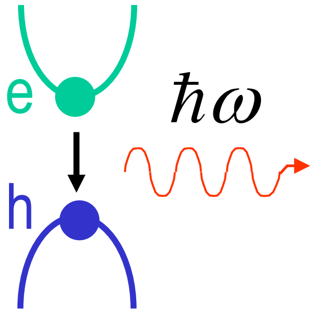
High carrier density and **high photon density** in an **active material** within a **small-volume optical resonator**

4

1. **Electrical confinement** (p-n heterostructure)
2. **Optical confinement** (single-mode waveguide)
3. **Gain** (quantum-confined material)
4. **Feedback** (distributed Bragg grating)

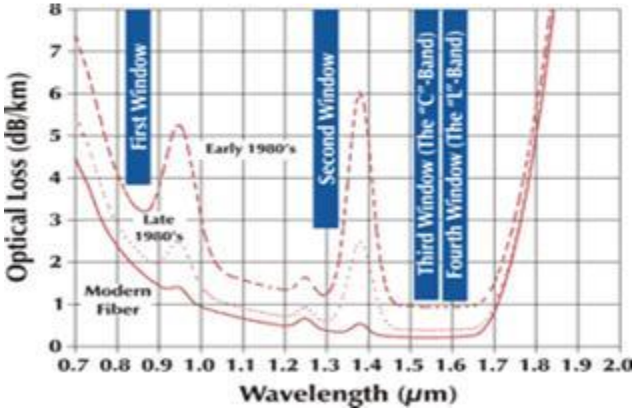
Semiconductor material basic requirements for photonic devices

- Optical gain, light emission (direct band gap) ...



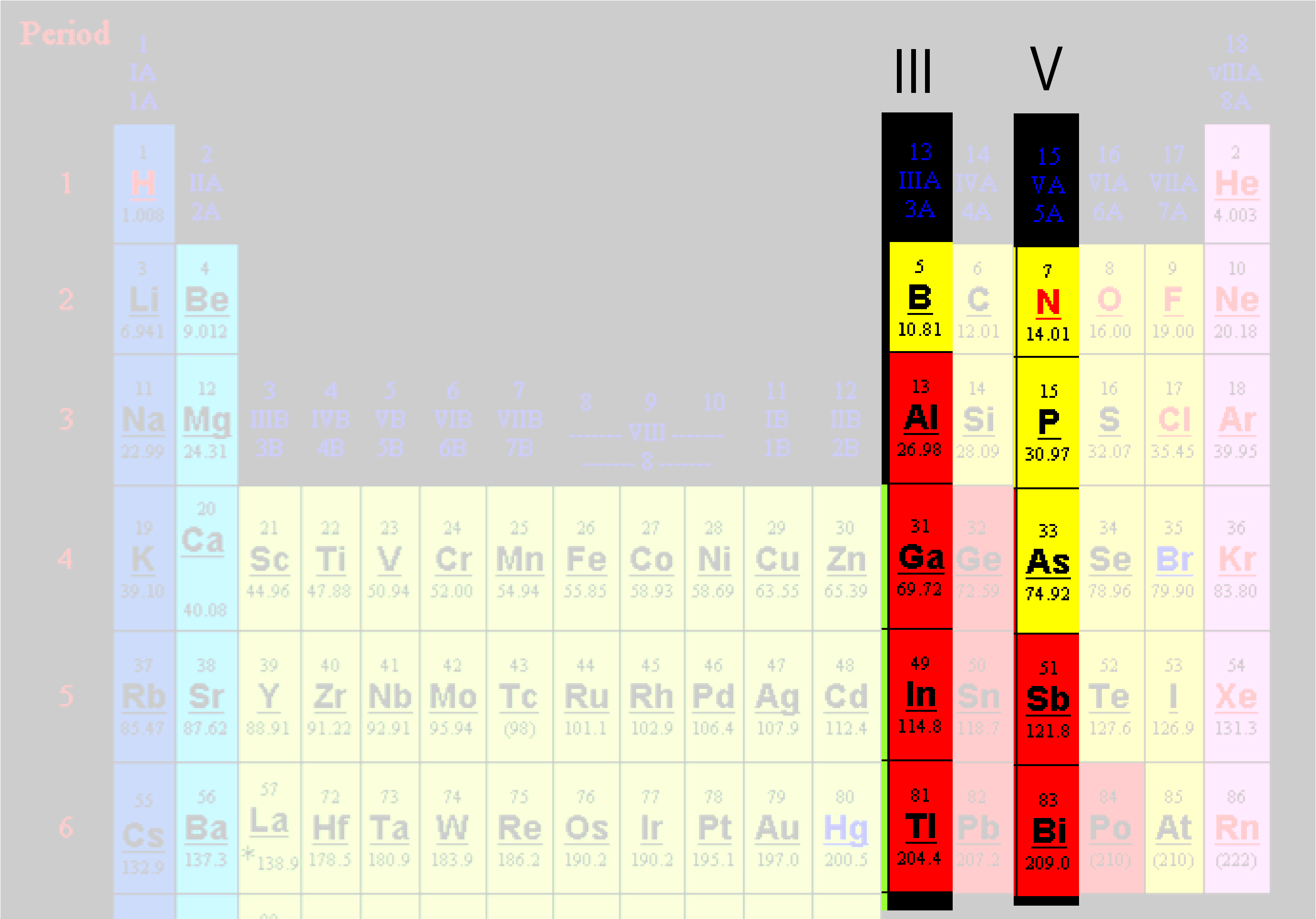
photon emission through e-h recombination

- ... at wavelength of interest: λ = 1,3 μm e 1,55 μm



- compatibility with semiconductor substrates: Si, GaAs, InP

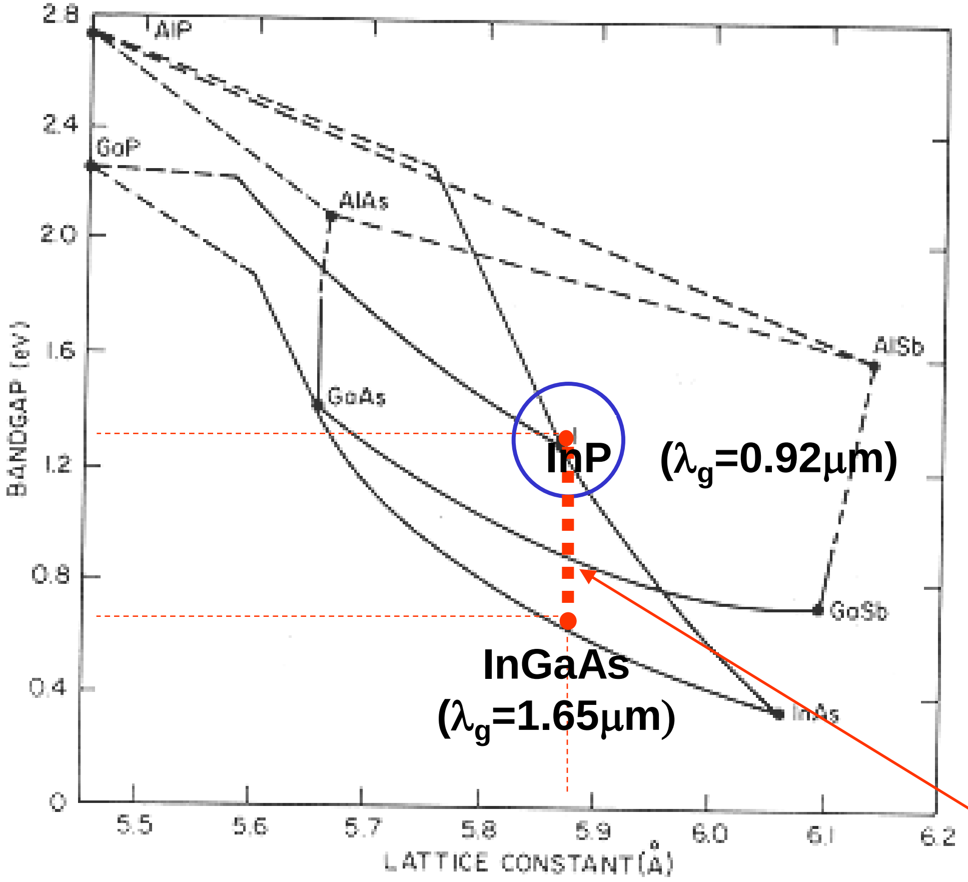
III-V semiconductor materials



There are no single elements or binary compounds compatible with commercial substrates and emitting light at 1.3 μm e 1.55 μm.
Semiconductor alloys of III-V elements are the best materials for photonic devices.

Quaternary alloy InGaAsP

T. P. Pearsall, GaInAsP Alloy Semiconductors, Wiley (1982)



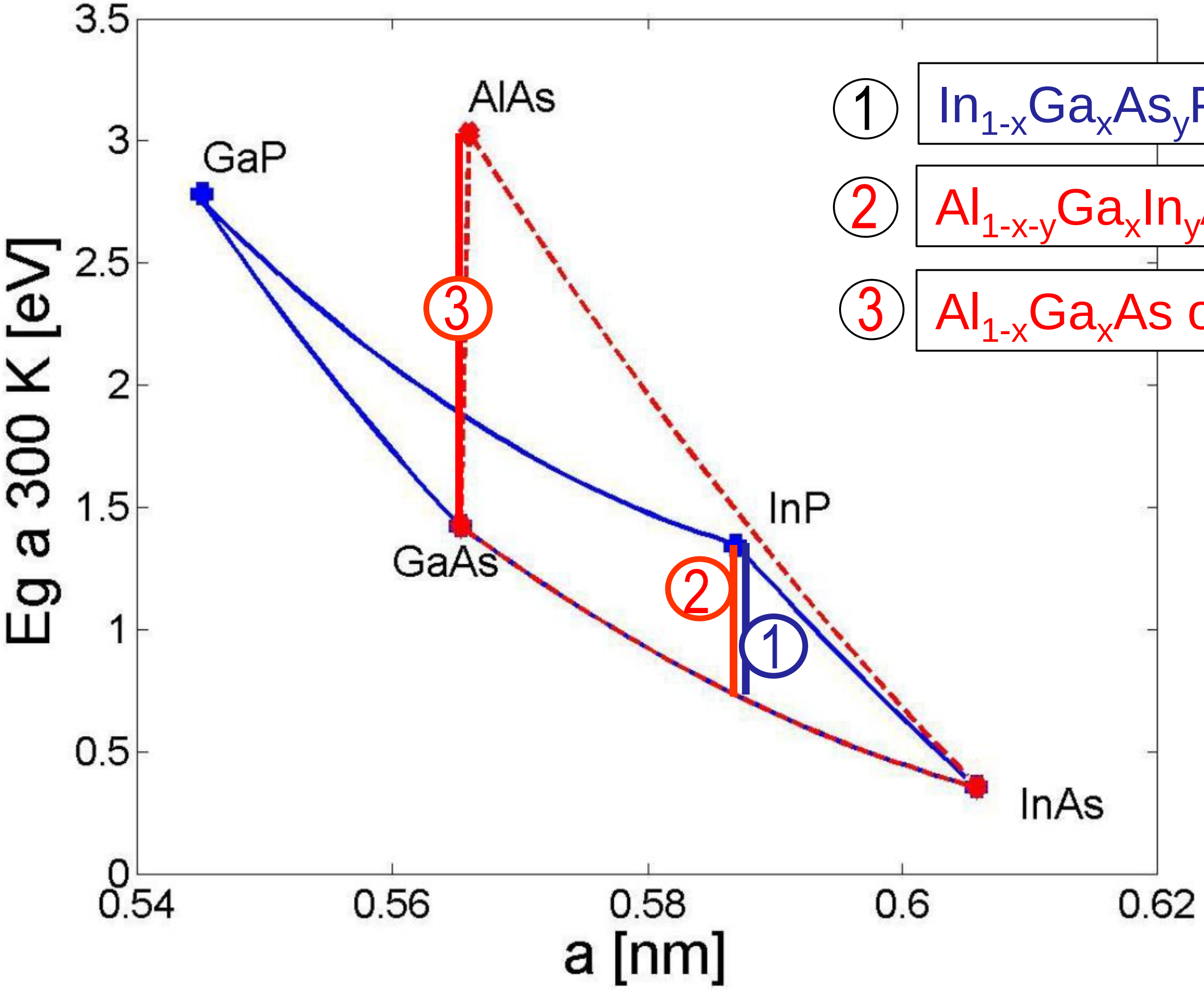
Variation of the bandgap as a function of lattice constant for III–V binary and alloy semiconductors

$In_{1-x}Ga_xAs_yP_{1-y}$ alloy cover all the spectral range required for optical telecom

- High quality material
- Established growth techniques and material processing
- Suited for active devices (lasers, amplifiers, modulators, ...) and passive structures (waveguides, couplers, ...)

$In_{1-x}Ga_xAs_yP_{1-y}$
lattice matched to InP
(λ_g=0.92 - 1.65µm)

Further alloy systems

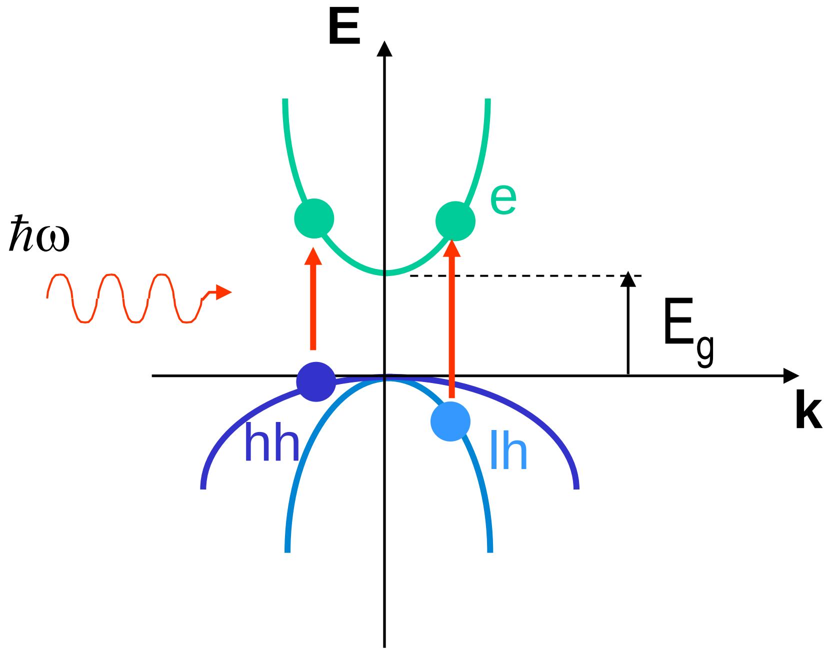


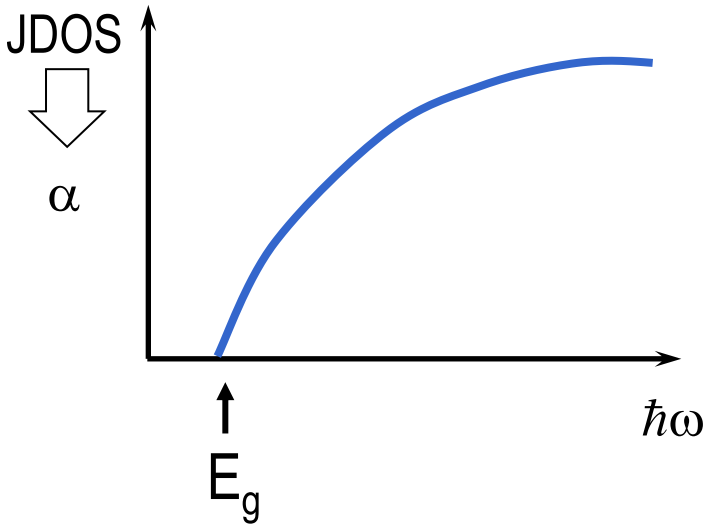
① $In_{1-x}Ga_xAs_yP_{1-y}$ on InP

② $Al_{1-x-y}Ga_xIn_yAs$ on InP

③ $Al_{1-x}Ga_xAs$ on GaAs

(Basic) Optical properties of semiconductors





Three bands are involved in optical transitions:

- Electrons — Conduction Band
- Heavy holes
- Light holes

} Valence Band

$$m_{hh}^{\;*} > 9\, m_e^{\;*}$$

$$m_{lh}^{\;*} \cong m_e^{\;*}$$

Joint density of states (available for optical transitions) is a square root function of the energy in excess of the energy gap

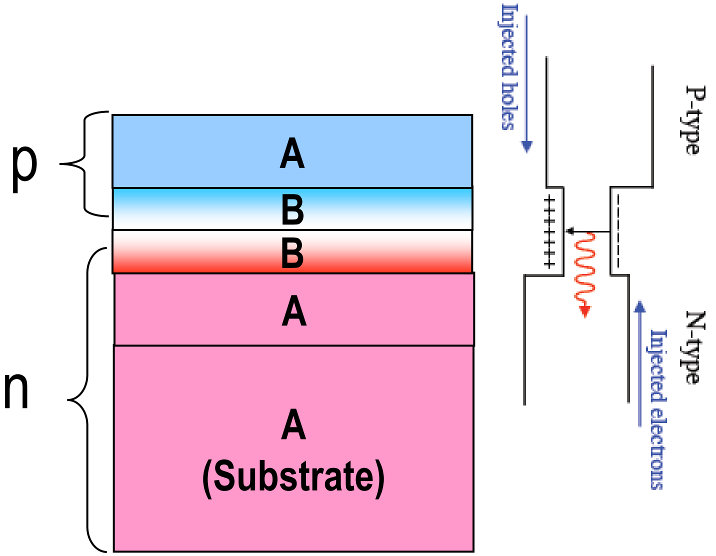
$$JDOS \propto \sqrt{\hbar\omega - E_g}$$

Semiconductor Heterostructures

Double Heterostructure (DH)

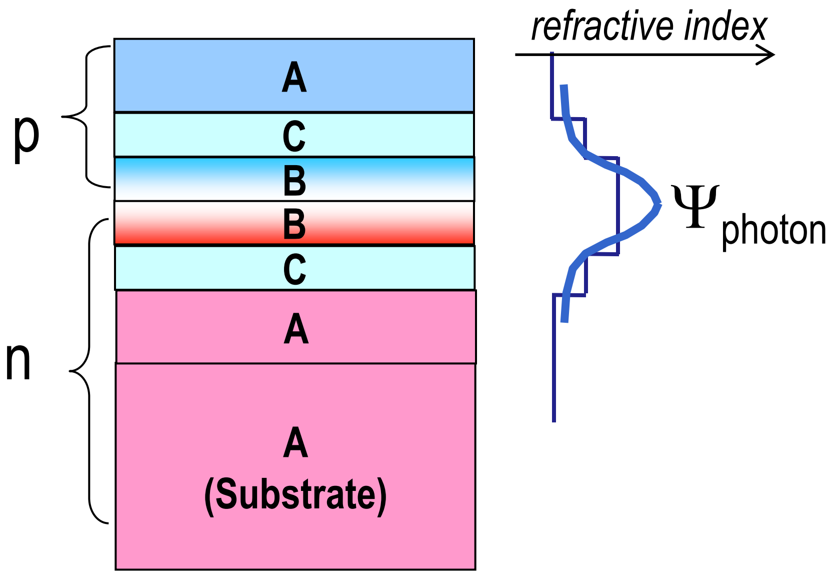
$\lambda_{ph} > \lambda_e$ ➡

Separate Confinement Heterostructure (SCH)



E_g(A)> E_g(B)

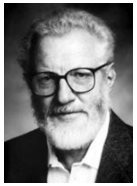
e-h confinement



E_g(A)> E_g(C))> E_g(B) , n(A)< n(C) < n(B)

Photon confinement

Combination of layers of different crystalline semiconductors.



H. Kroemer, Varian associates 1963
(Nobel Prize in Physics, 2000)

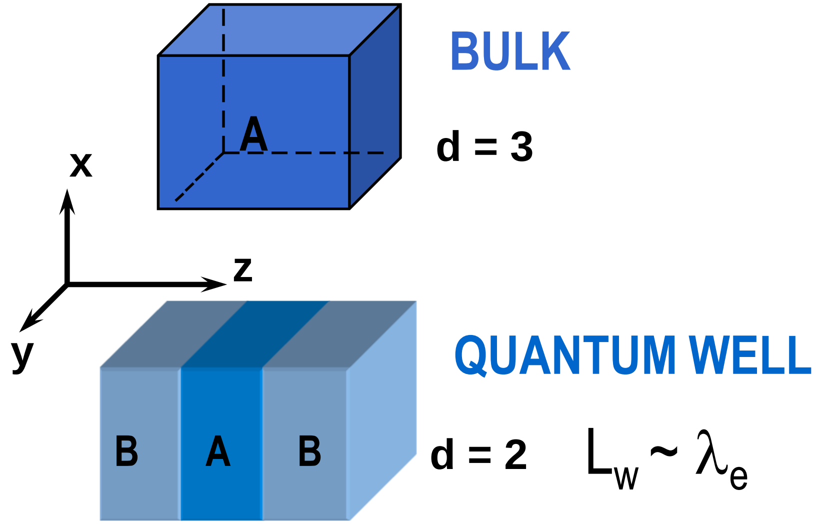
The idea was experimentally demonstrated using the Liquid Phase Epitaxy (LPE)

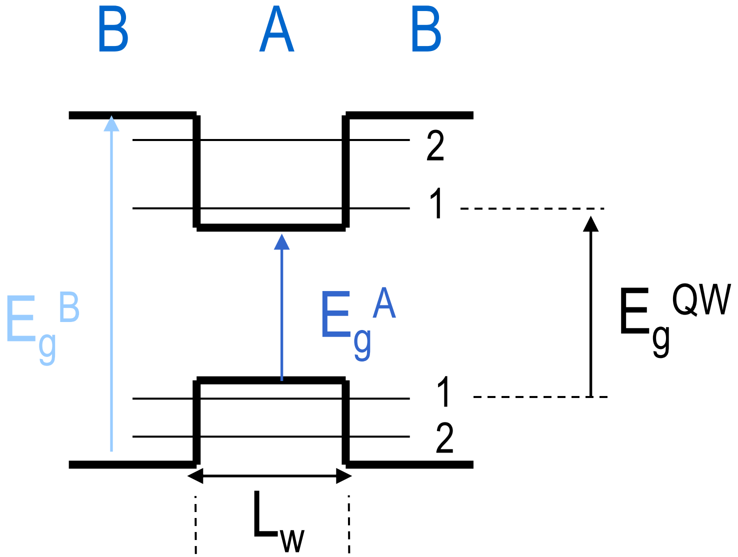
Quantum Wells

Quantum-Size Double Heterostructure (Quantum Well) is a planar waveguide for electrons

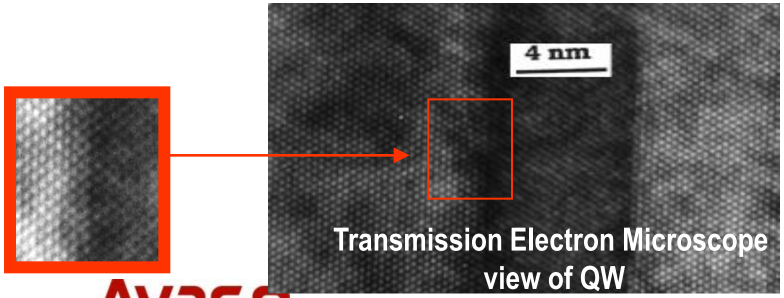
C. H. Henry, Bell Labs 1972

The idea was experimentally demonstrated in 1974 using the newly developed Molecular Beam Epitaxy (MBE).





QW is now a widely spread quantum product based in atomic-scale technology



Transmission Electron Microscope view of QW

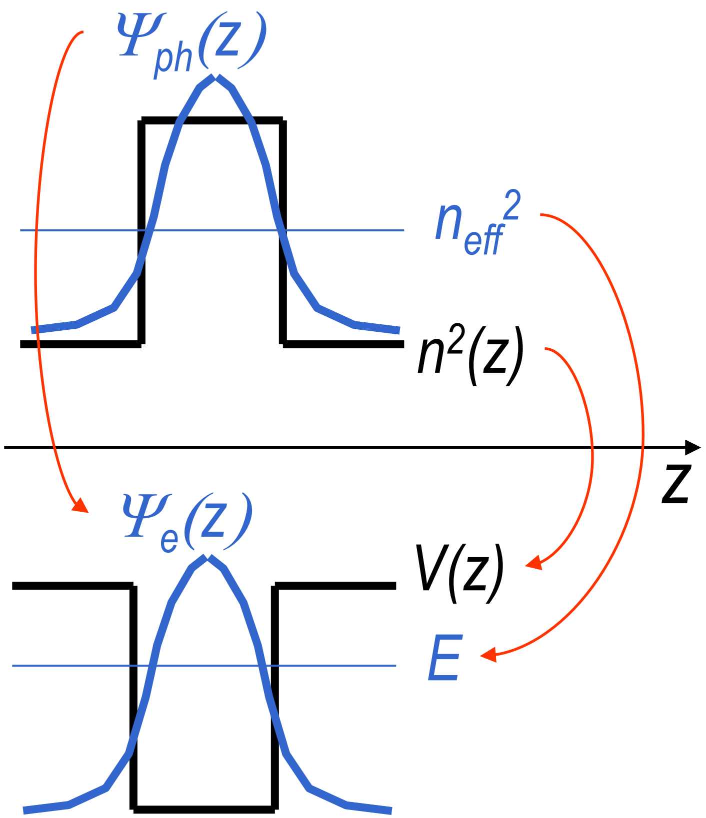
Photon wave eqn. vs. Electron wave eqn.

Helmholtz equation (*photon*)

$$\left[\frac{d^2}{dz^2}+k_0^2n^2(z)\right]\psi(z)=n_{eff}^2\psi(z)$$

Schroedinger equation (*electron*)

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dz^2}+V(z)\right]\psi(z)=E\psi(z)$$



$$n^2(z) \Rightarrow -V(z)$$

cladding ⇒ barrier

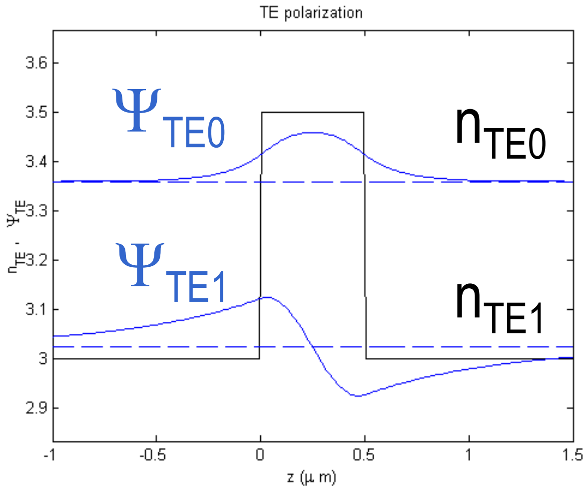
core ⇒ well

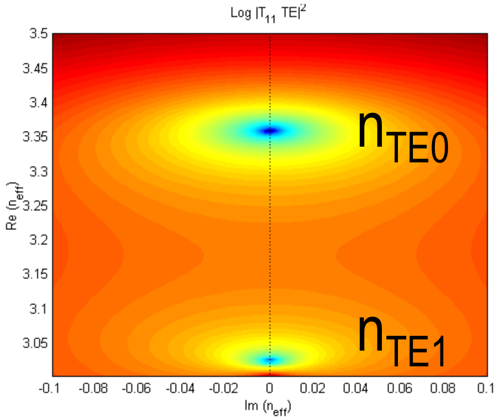
refractive index ridges confine photons (**optical waveguides**)

potential wells confine electrons (**quantum wells**)

Eigenfunction/Eigenvalues Calculation

Optical Waveguide

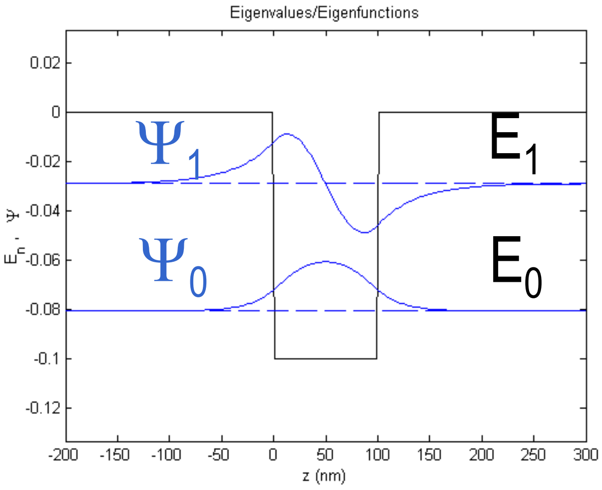


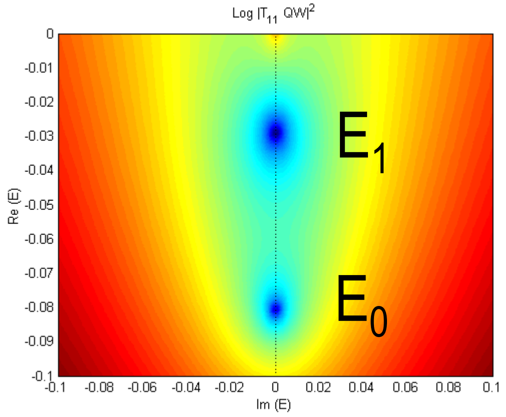


$$\Psi_{TE}(z^-)=\Psi_{TE}(z^+)$$

$$\frac{\partial}{\partial z}\Psi_{TE}(z^-)=\frac{\partial}{\partial z}\Psi_{TE}(z^+)$$

Quantum Well

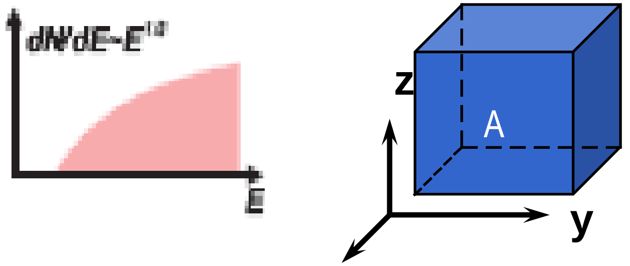




$$\Psi(z^-)=\Psi(z^+)$$

$$\frac{1}{m(z^-)}\frac{\partial}{\partial z}\Psi(z^-)=\frac{1}{m(z^+)}\frac{\partial}{\partial z}\Psi(z^+)$$

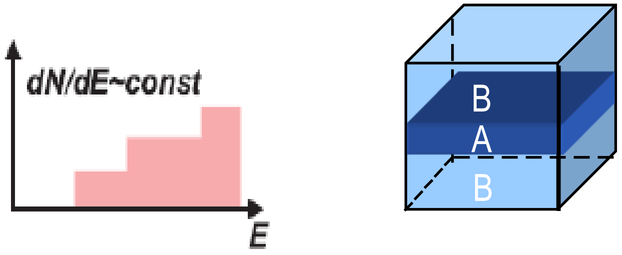
Reduced dimensionality structures



BULK

d = 3

Q.M. **E.M.**

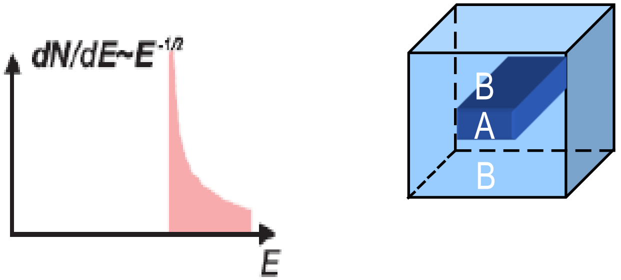


QUANTUM WELL ⟷ **PLANAR WAVEGUIDE**

d = 2

$L_z \sim \lambda_e$

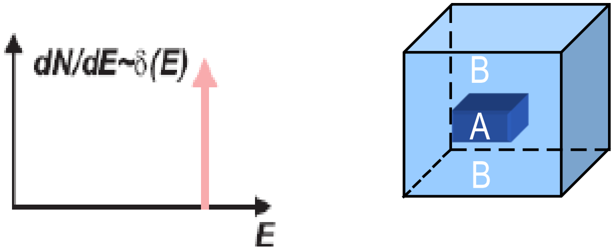
1975: R.Dingle and C.Henry
USA Patent Application



QUANTUM WIRE ⟷ **CHANNEL WAVEGUIDE**

d = 1

$L_z, L_y \sim \lambda_e$



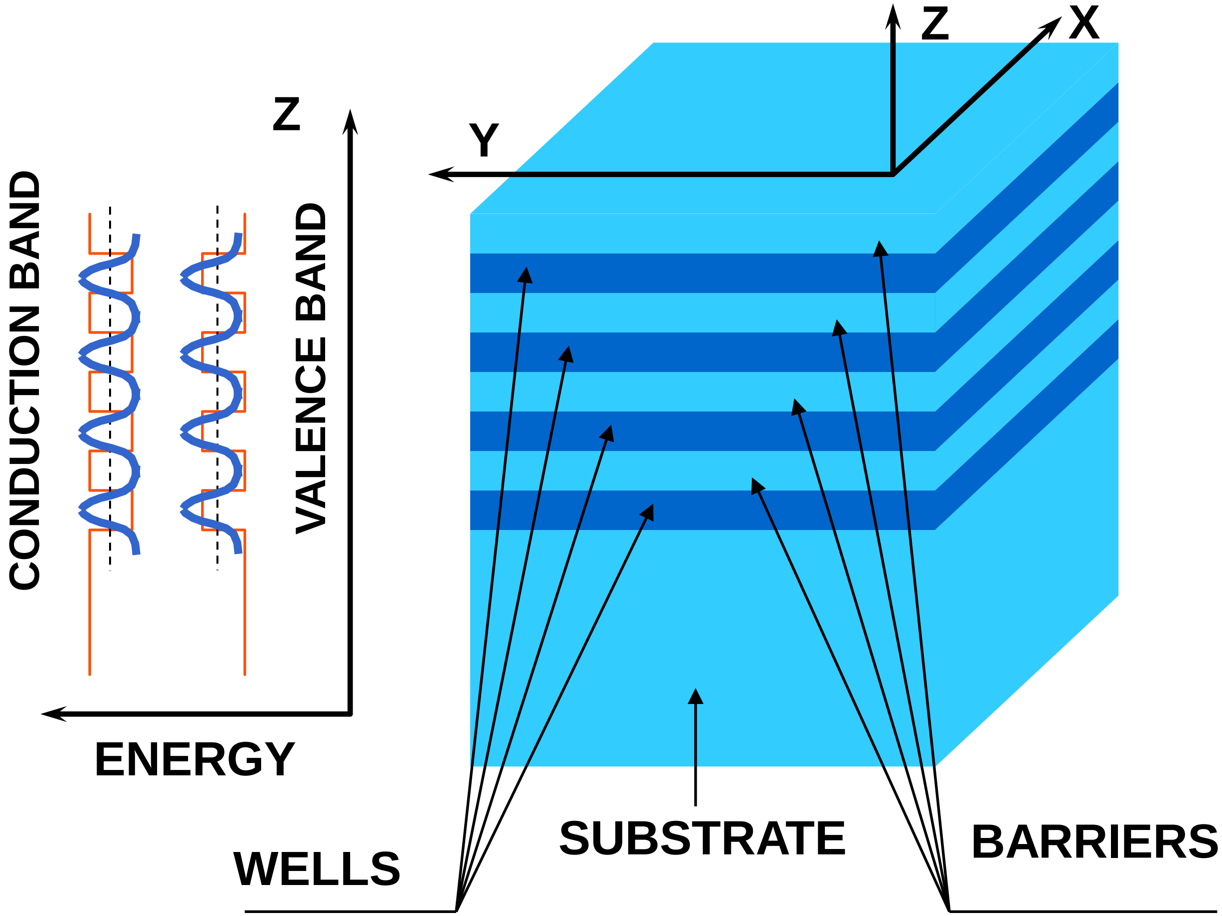
QUANTUM DOT ⟷ **OPTICAL RESONATOR**

d = 0

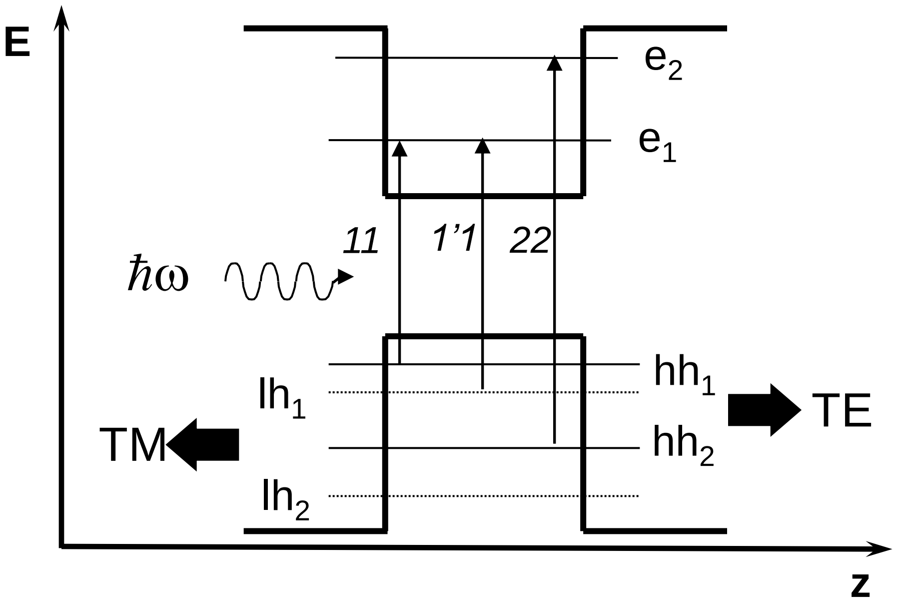
$L_z, L_y, L_x \sim \lambda_e$

MQW heterostructures

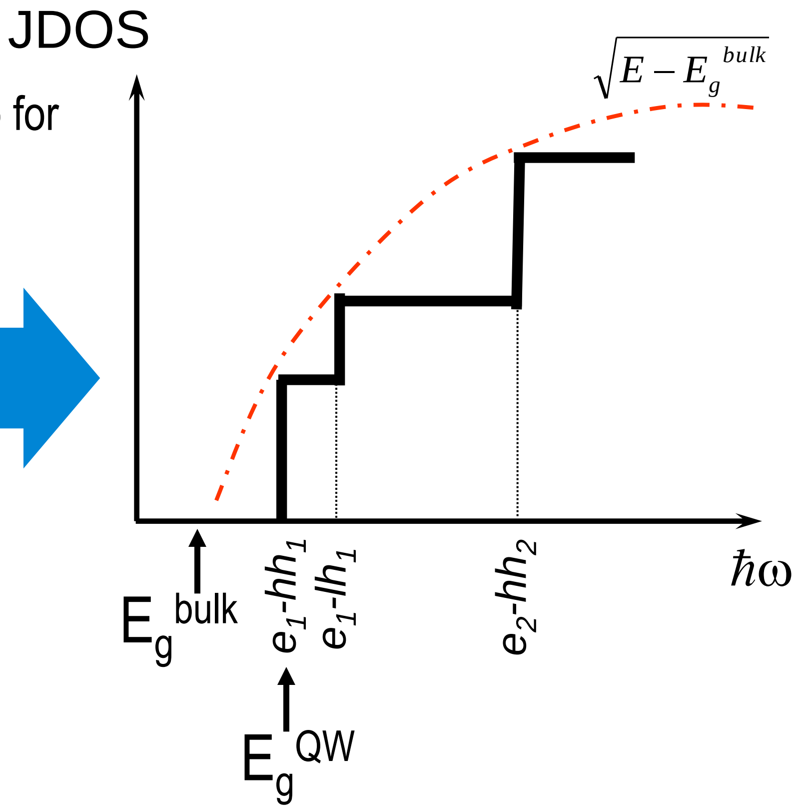
Multi Quantum Wells are stacks of **decoupled** QWs
(with sufficiently thick barriers): **enhancement of single QW effects**



QW band structure



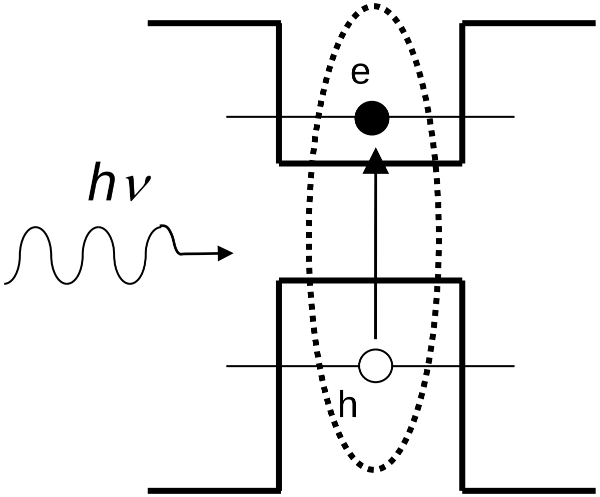
One step for every allowed transition



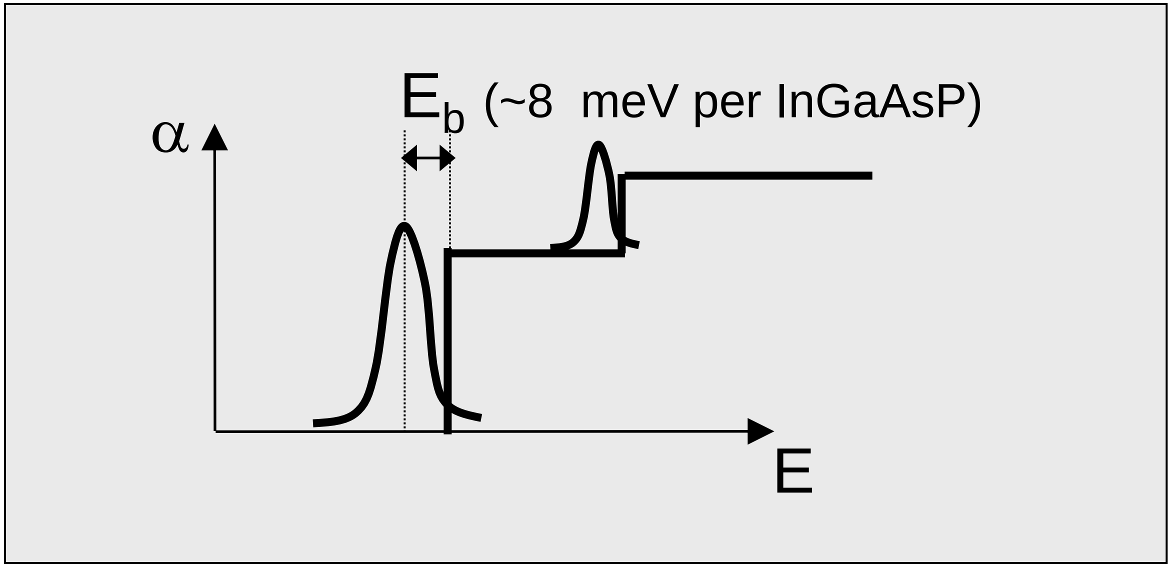
2D JDOS related features:
- Sharp absorption edge (2D JDOS)
- High differential gain
- Wide gain bandwith
- High electroabsorption efficiency (QCSE)
- Strong optical nonlinearities
- . . .

$$JDOS = \sum_{i\,j} \frac{\mu_{i\,j}}{\pi\,\hbar^2}\,\Theta\left(\hbar\omega - E_{i\,j}\right)$$

Excitons

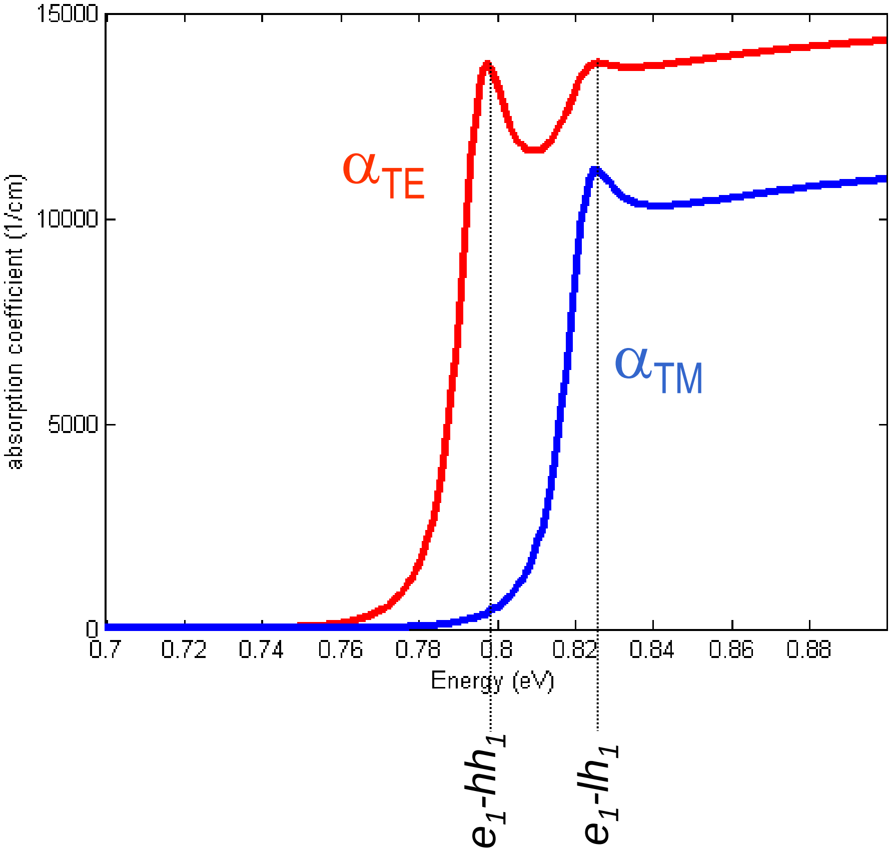


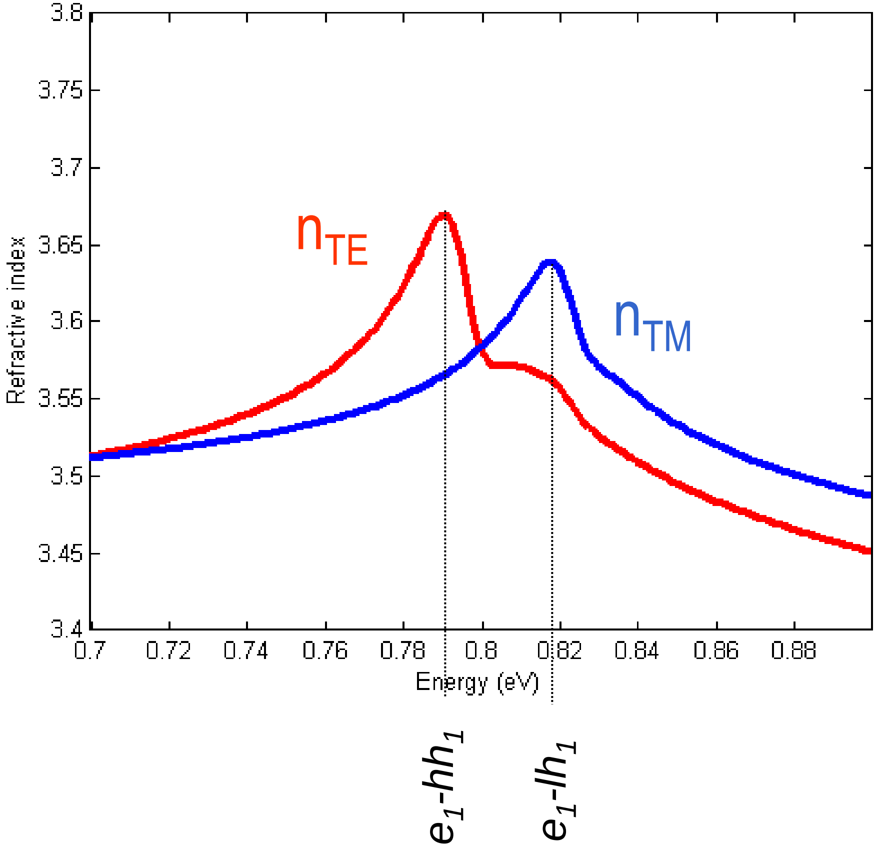
e - h semi-bound states (τ ~ 100 fs) which produce sharp absorption peaks detuned from the transition energies (absorption steps) by their binding energy



QW optical properties

$$\alpha(\omega) \propto JDOS + exciton\ \ state \Rightarrow n(\omega) = 1 + \frac{c}{\pi} \mathrm{P}\int_0^\infty \frac{\alpha(\omega')d\omega'}{\omega'^2 - \omega^2} \Rightarrow \hat{\mathrm{n}}(\omega) = n(\omega) + i\,\frac{\alpha(\omega)c}{2\omega}$$





Strong dichroism ⇒

Polarisation selection rules:

TE: 3/4 hh, 1/4 lh

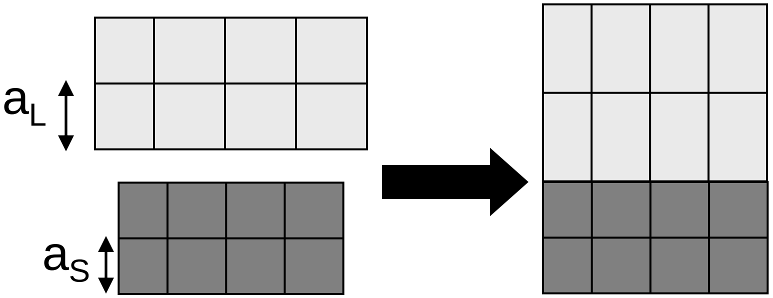
TM: 0 hh, 1 lh

Strain(1)

The epitaxial layer can be grown with a lattice parameter slightly different from the substrate lattice parameter (lattice mismatch).

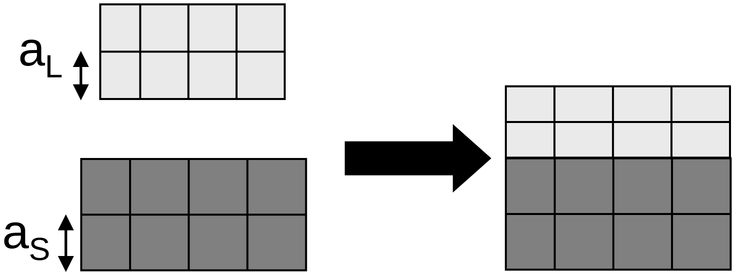
$$m = \frac{a_L - a_S}{a_S} \quad , a_L = \text{lattice parameter of the epitaxial layer}$$

$$a_S = \text{lattice parameter of the substrate}$$



compressive strain

m>0

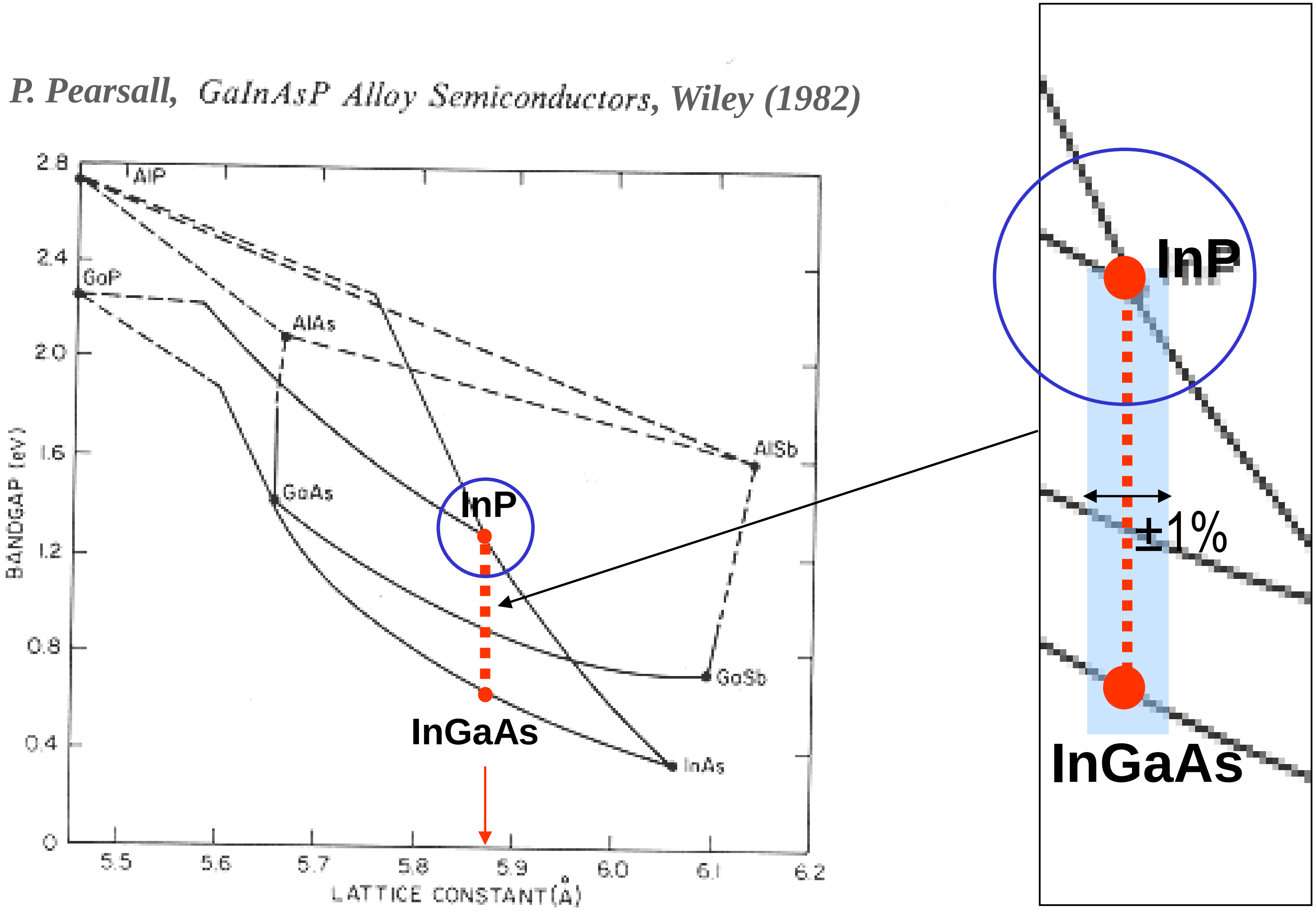


tensile strain

m<0

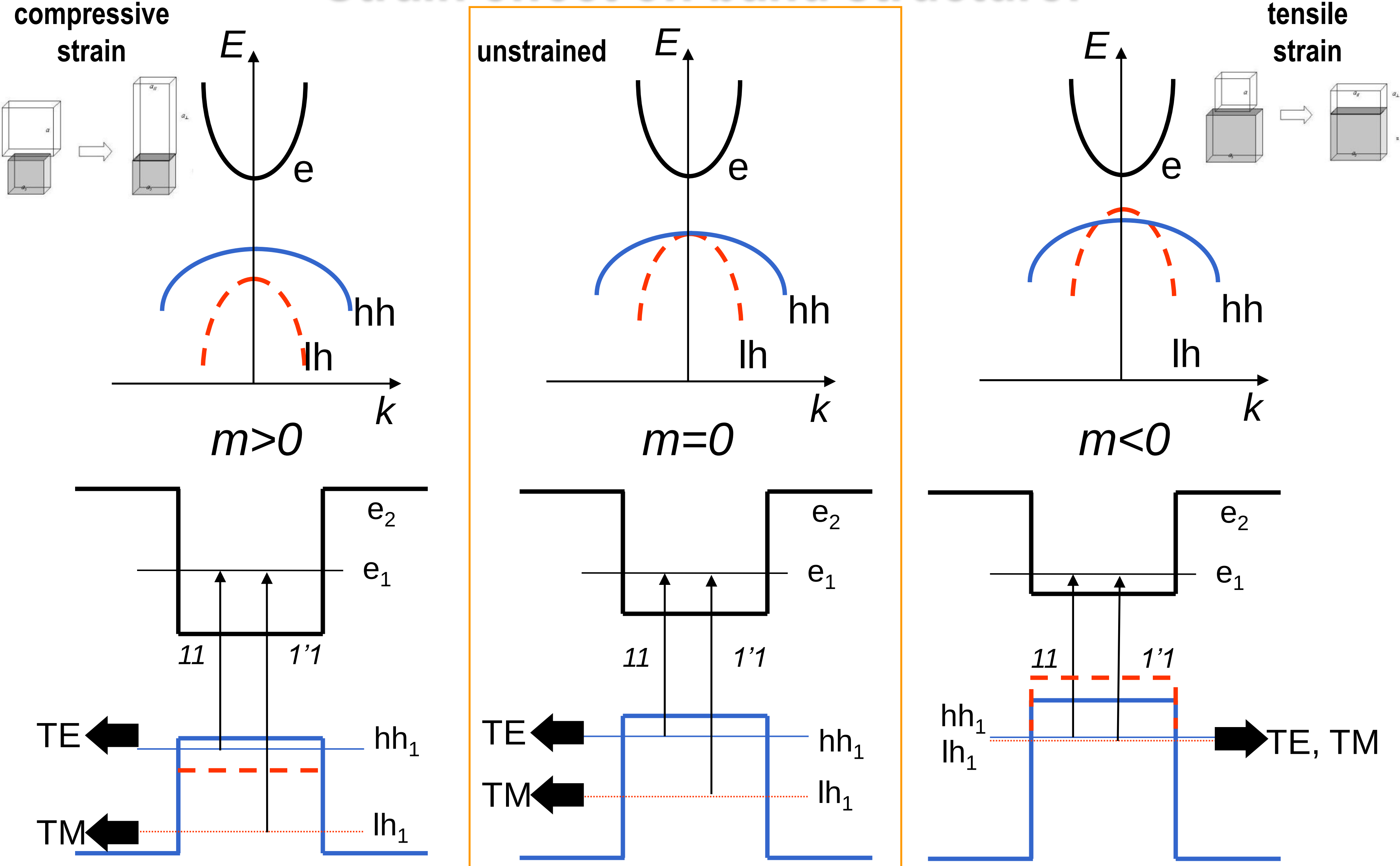
Strain(2)

T. P. Pearsall, GaInAsP Alloy Semiconductors, Wiley (1982)



Variation of the bandgap as a function of lattice constant for III–V binary and alloy semiconductors

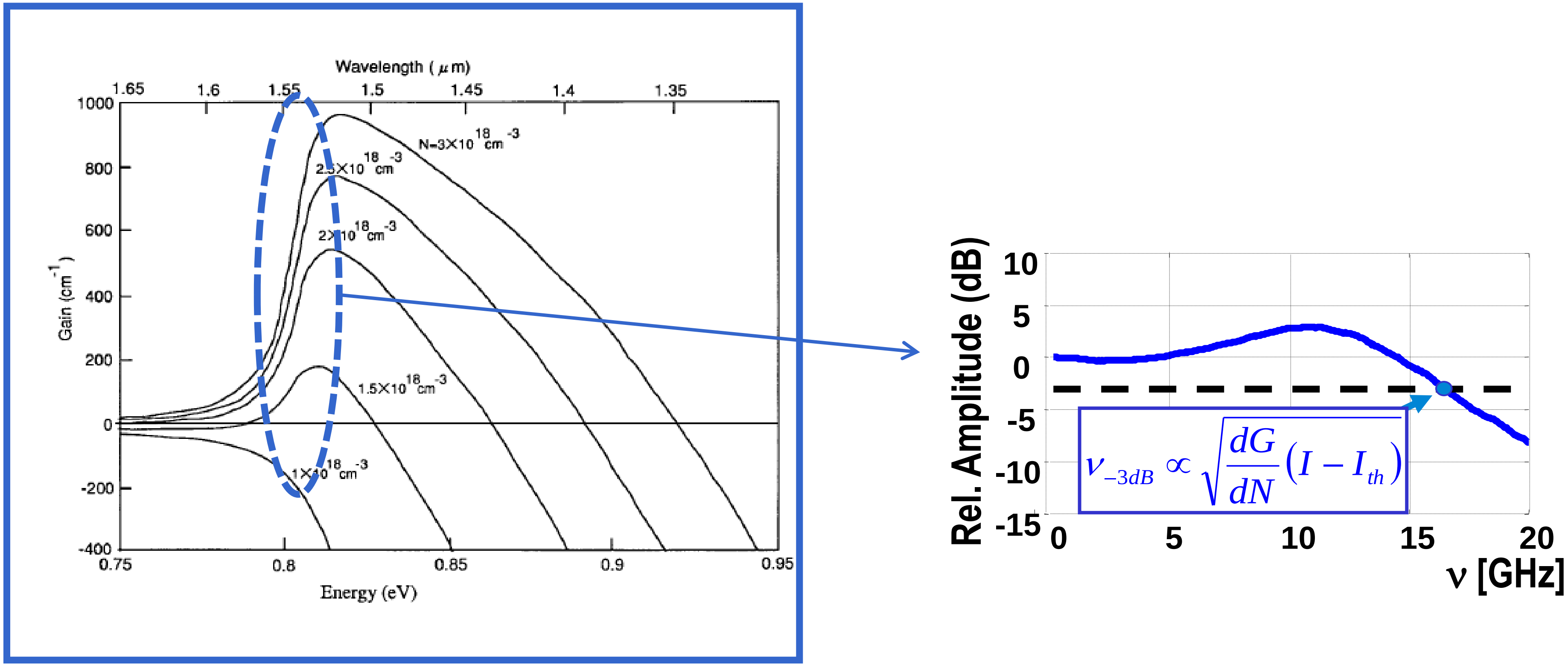
Strain effect on band structure:



Low escape time
High T_0 (low thermal dependence)
High-speed uncooled Lasers

Low dichroism
Polarization-independent devices

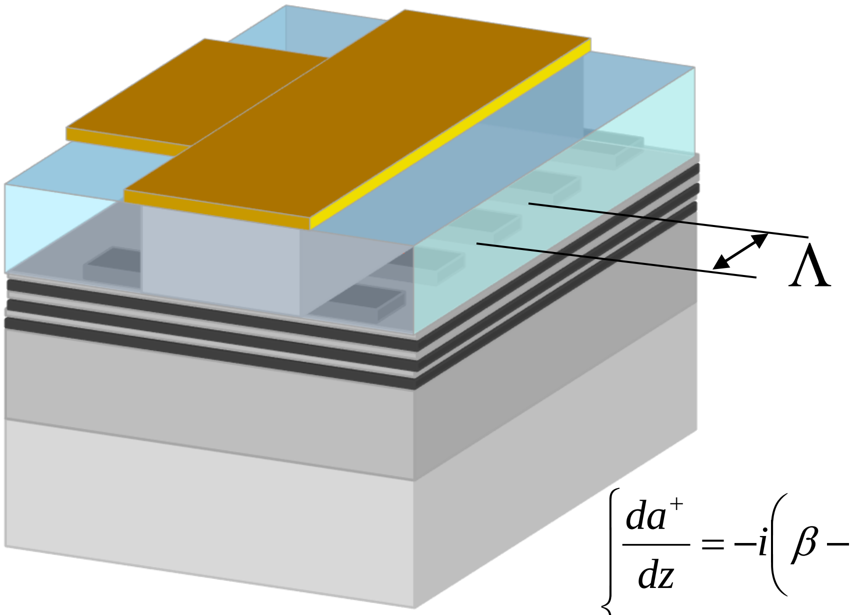
Optical gain in MQW

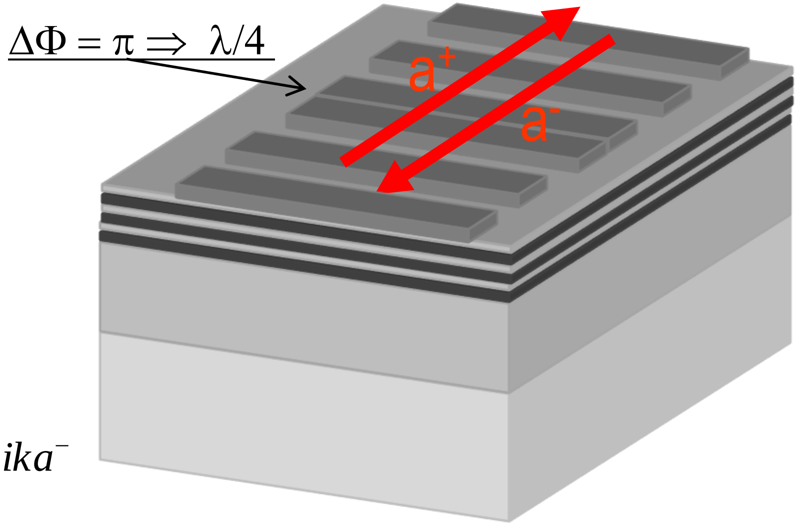


$$\nu_{-3dB} \propto \sqrt{\frac{dG}{dN}\left(I - I_{th}\right)}$$

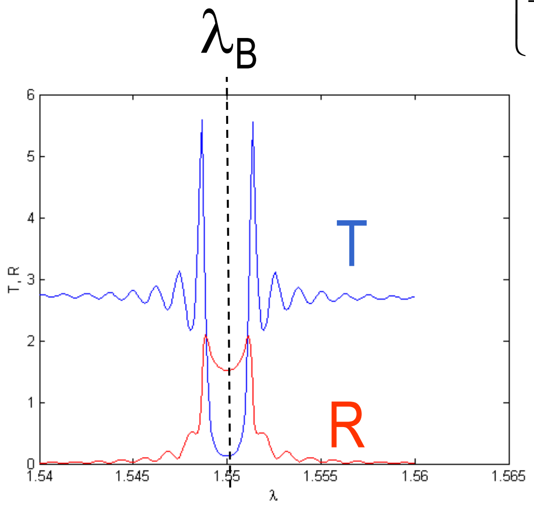
- **high differential gain (dG/dN)** ⇦ step-like shape of density of states
- **wider spectral bandwidth** ⇦ deep penetration of Fermi function

Distributed Feedback

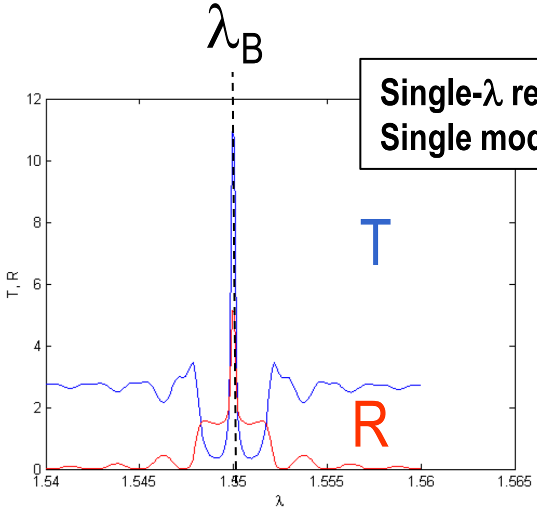




$$\left\{ \begin{array}{l} \dfrac{da^+}{dz} = -i\left(\beta - \dfrac{\pi}{\Lambda}\right)a^+ - ika^- \\ \dfrac{da^-}{dz} = ika^+ + i\left(\beta - \dfrac{\pi}{\Lambda}\right)a^- \end{array} \right.$$

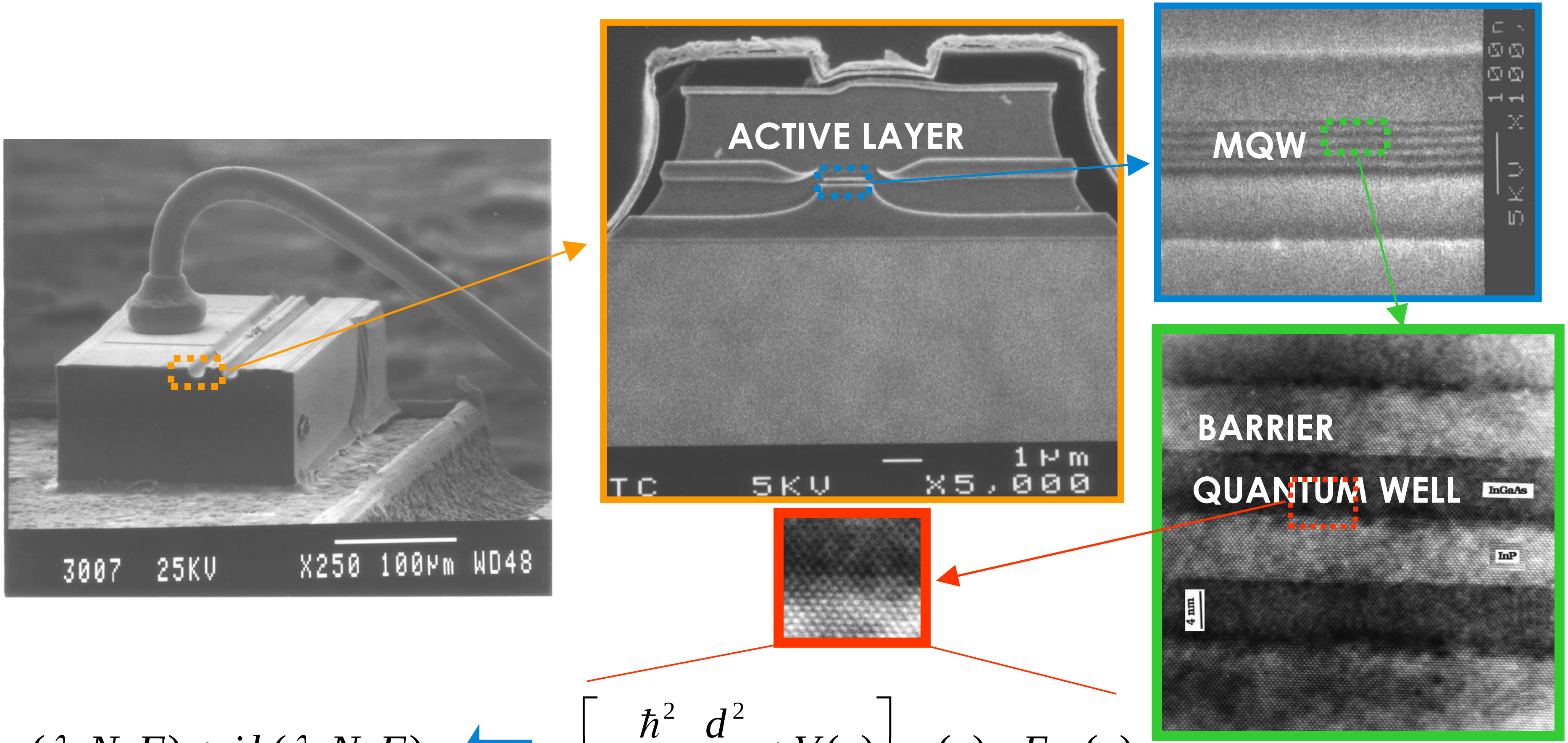


$$\left\{ \begin{array}{l} \kappa = 65\ cm^{-1} \\ \Lambda = 0.24\,\mu m \\ \beta = \dfrac{2\pi}{\lambda}\cdot\left(3.2 + 3.4\times10^{-4}i\right) \end{array} \right.$$



Single-λ reflectivity:
Single mode laser

Quantum Wells:
Atomic-Controlled Artificial Structures



$$n(\lambda,N,F)+i\,k(\lambda,N,F) \Leftarrow \left[-\frac{\hbar^2}{2m}\frac{d^2}{dz^2}+V(z)\right]\psi(z)=E\psi(z)$$

Control of Optical Properties through atomic-scale technology
Quantum Well requires <u>sub-monolayer manufacturing</u> control achievable with Molecular Beam Epitaxy or Metal Organic Chemical Vapor Deposition.

Thanks for your attention!

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