Semiconductor Lasers for Optical Communication (part 1)

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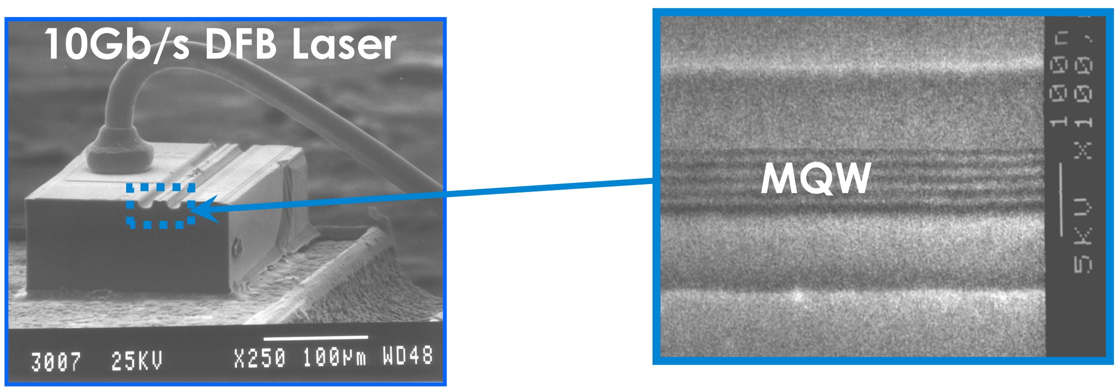
Turin Technology Centre



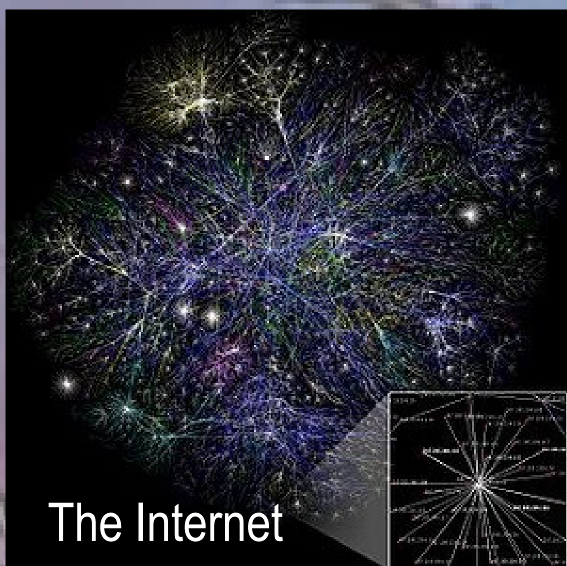
AVAGO TECHNOLOGIES

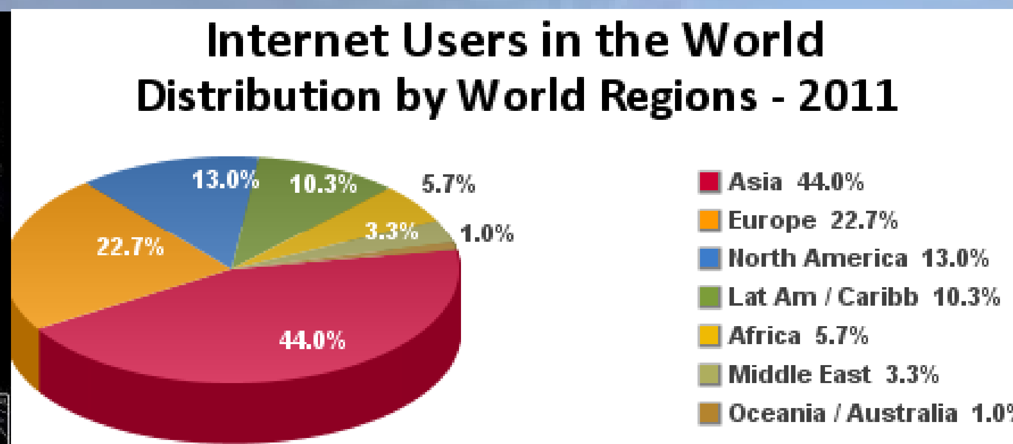
Outline

1) Background and Motivation
    - Communication Traffic Growth
    - Photonics evolution
2) Optical Feedback and Active materials
    - Distributed FeedBack Lasers(DFB)
    - Strained Multiple Quantum Wells (MQW)
3) Avago snapshot
    - Turin Technology Center (TTC)

Communication Growth

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





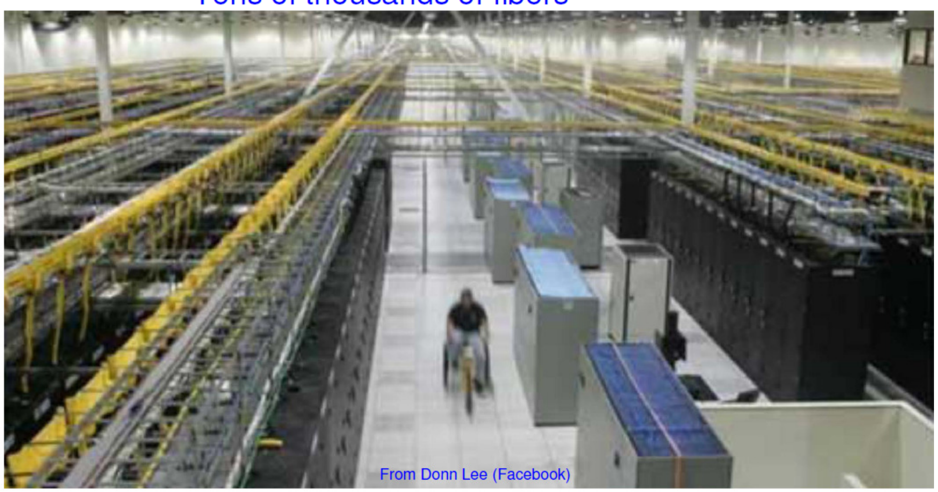
Source: Internet World Stats - www.internetworldstats.com/stats.htm
Basis: 2,095,006,005 Internet users on March 31, 2011 (30.2% world population)
Copyright © 2011, Miniwatts Marketing Group

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 today (8.7×10^{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

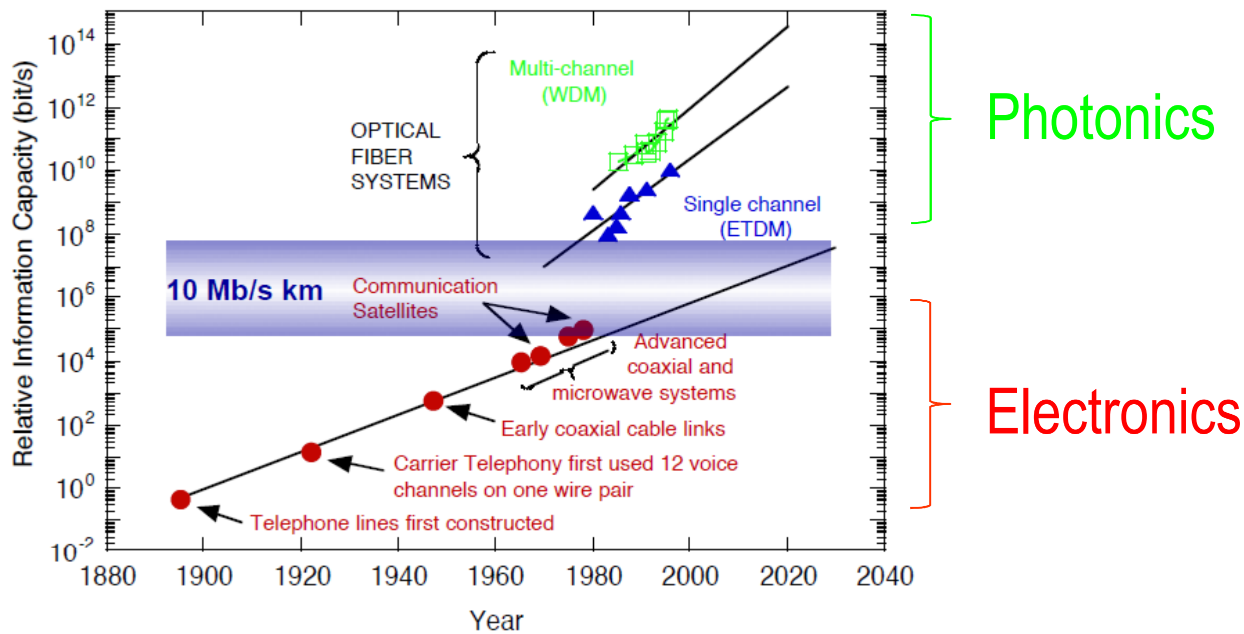
=

FACEBOOK [(3)] :

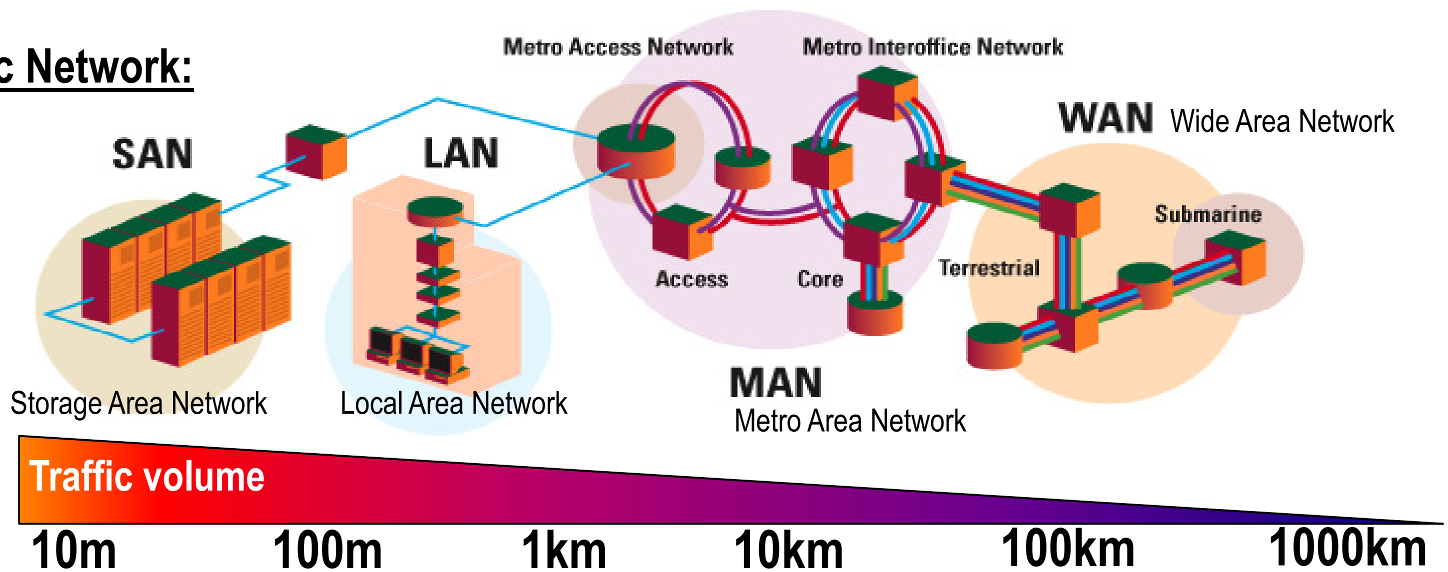
- 800 milion active users worldwide
- 20.6 miliion active users in Italy
- 8 billion minute/day

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

Photonics in Optical Communication



Today Photonic Network:



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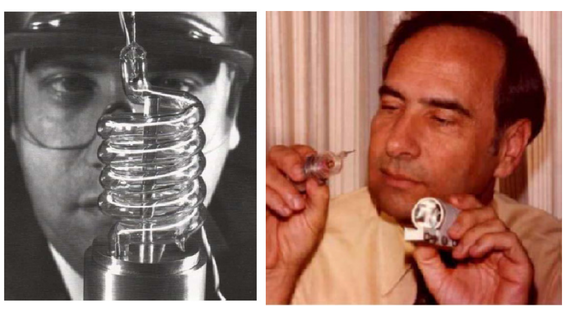
C. Coriasso – Nov 2011

Photonics in Optical Communication

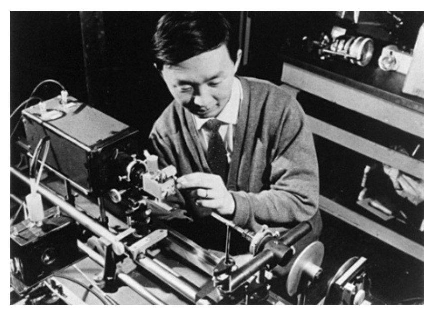
Photonics:
Science and technology of light

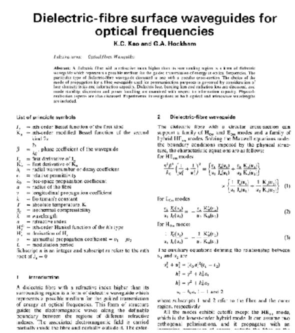
- Emission,
- Transmission,
- Processing (modulation, switching, amplification, …)
- Detection

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

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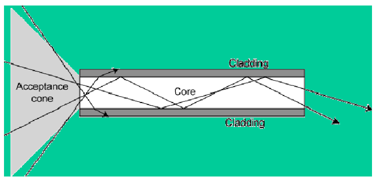
Fiber Optics

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

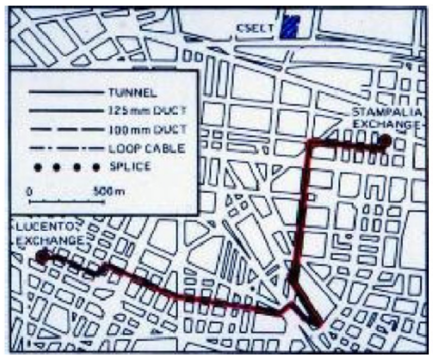
1970: Production of first fiber optic [Corning]

1976-77: First fiber optic networks

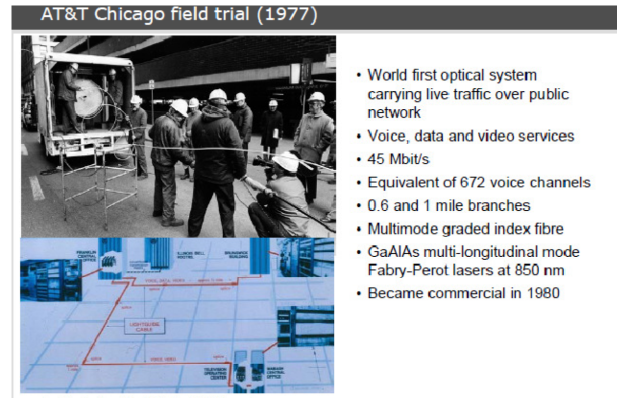
1988: First transoceanic fiber-optic cable (3148 miles, 40000 simultaeous telephone calls)



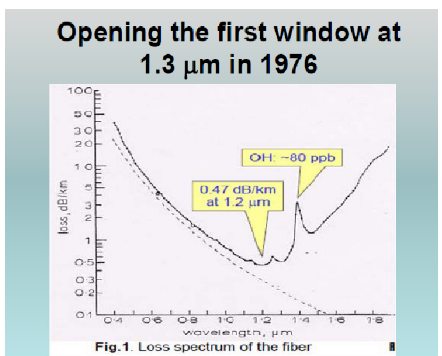
C. K. Kao receiving his Nobel Prize Stockholm 2009

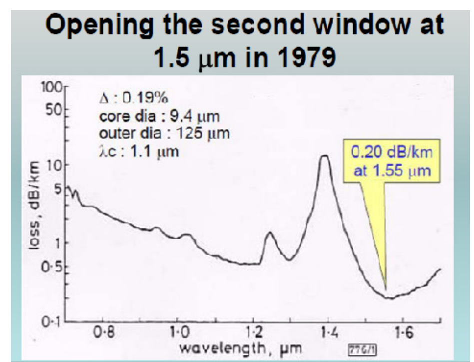


First operative optical cable in urban areas **Torino 1976**



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





Semiconductor LASER

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

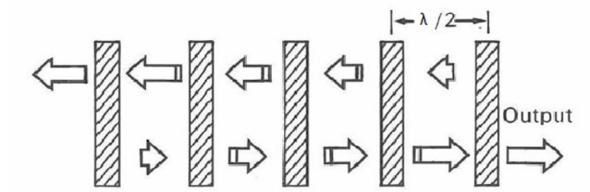
1977: Proposal of Vertical Cavity Surface Emitting Laser (VCSEL)

1984: First Realization of Strained MQW in semiconductor laser

1988: First Realization of VCSEL

2000: First Uncooled Telecom Lasers

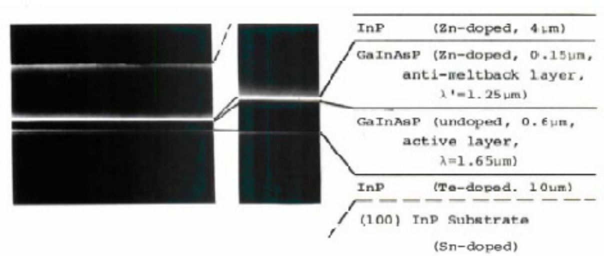
Theory of Distributed Feedback (DFB) Lasers
H. Kogelnik and C. V. Shank 1972



Two Modes Operation (for Refractive Index Coupling)

Z. Alferov receiving his Nobel Prize Stockholm 2000

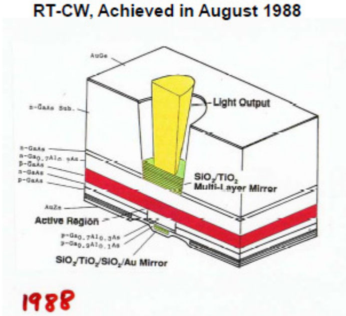
RT-CW Operation of 1.5µm Laser
~ GaInAsP/InP Laser ~



- 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



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).

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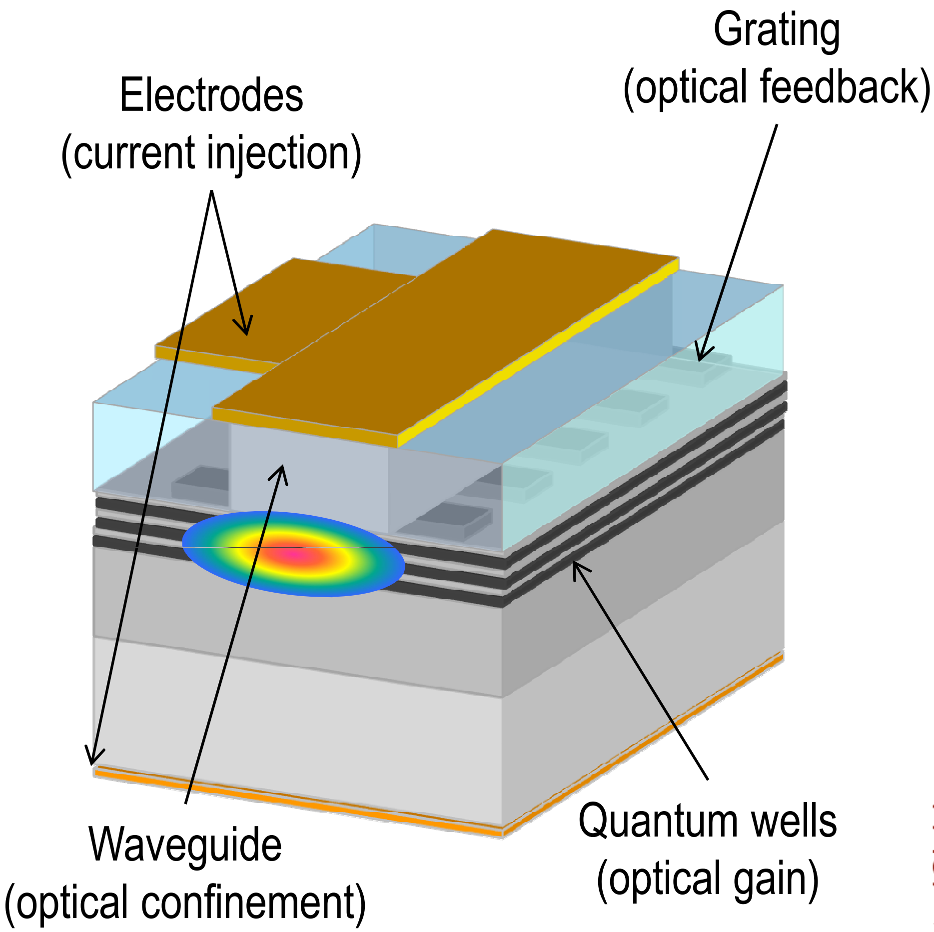
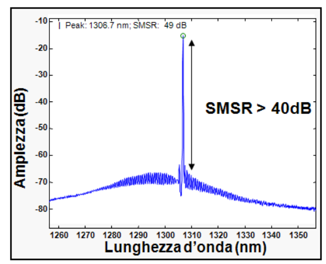
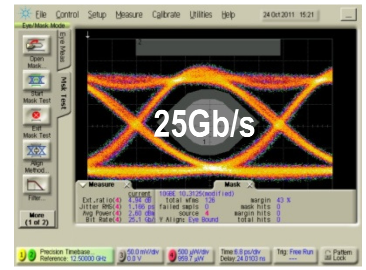
Laser requirements for optical communication



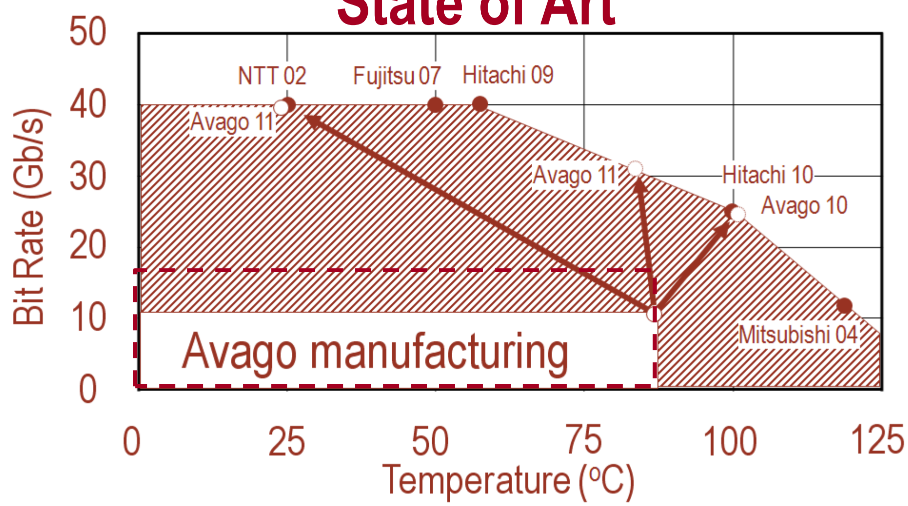
DFB MQW Laser

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





State of Art



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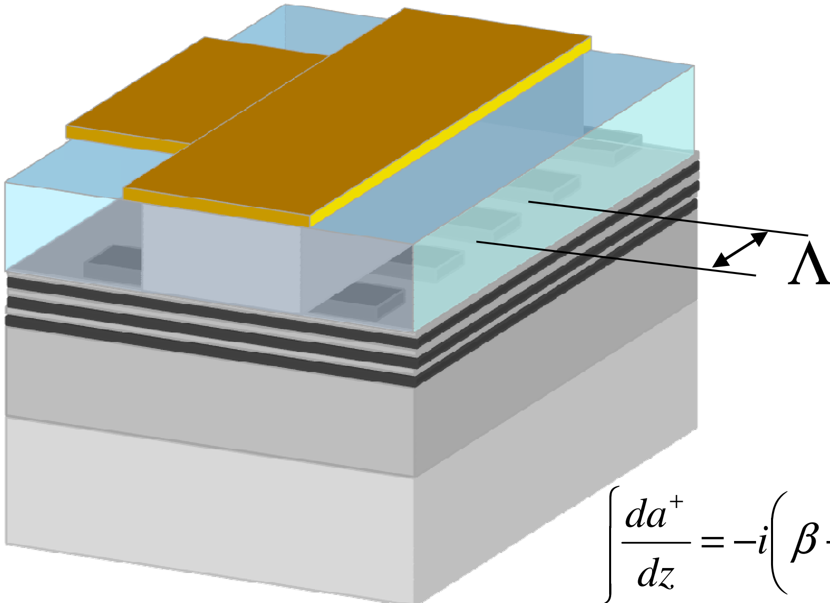
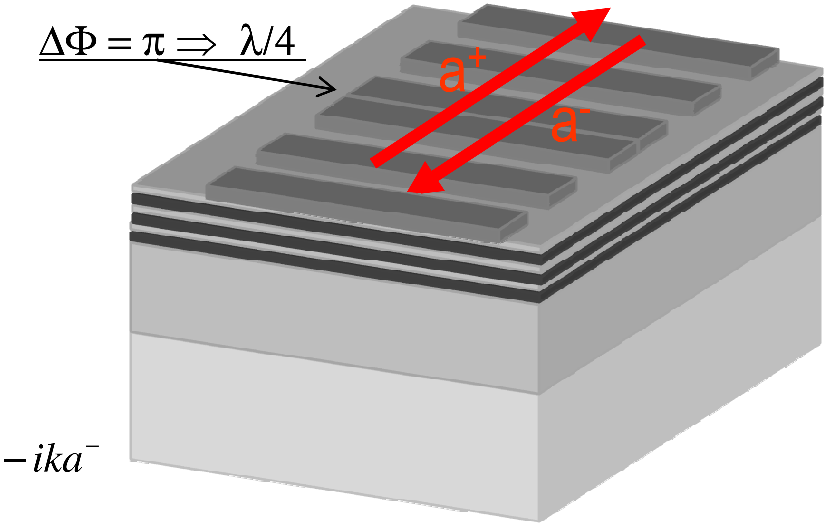
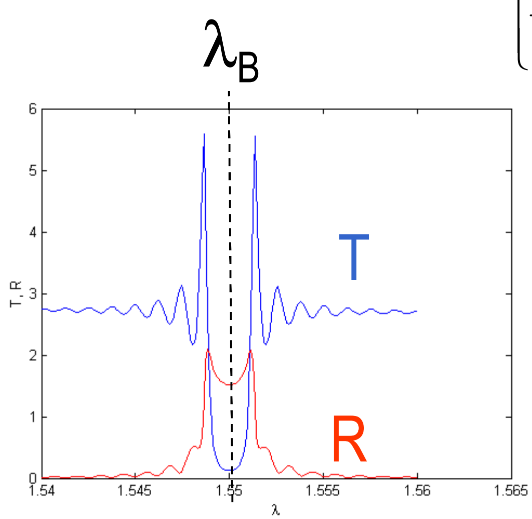
Distributed Feedback

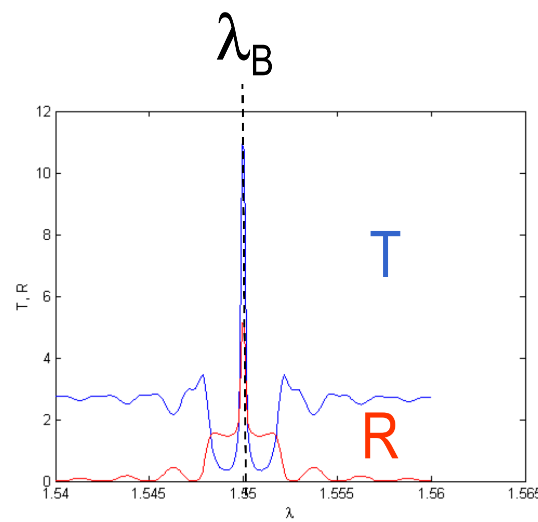




$$\begin{cases} \dfrac{da^+}{dz} = -i\left(\beta - \dfrac{\pi}{\Lambda}\right)a^+ - ika^- \\ \dfrac{da^-}{dz} = ika^+ + i\left(\beta - \dfrac{\pi}{\Lambda}\right)a^- \end{cases}$$



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



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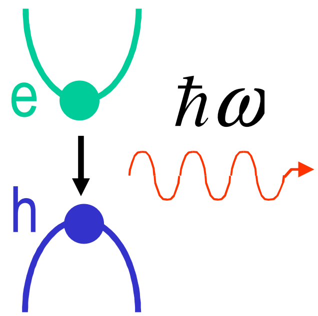
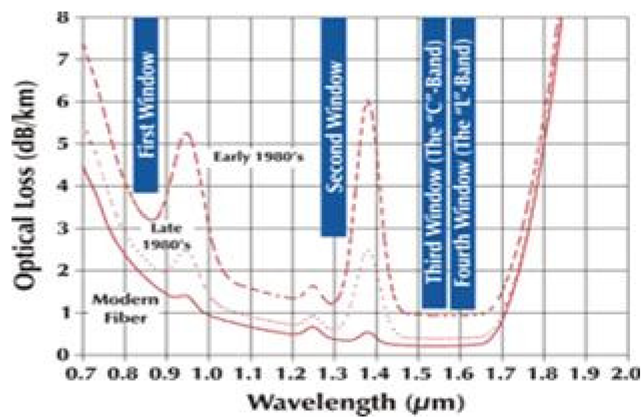
Semiconductor material basic requirements for photonic devices

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



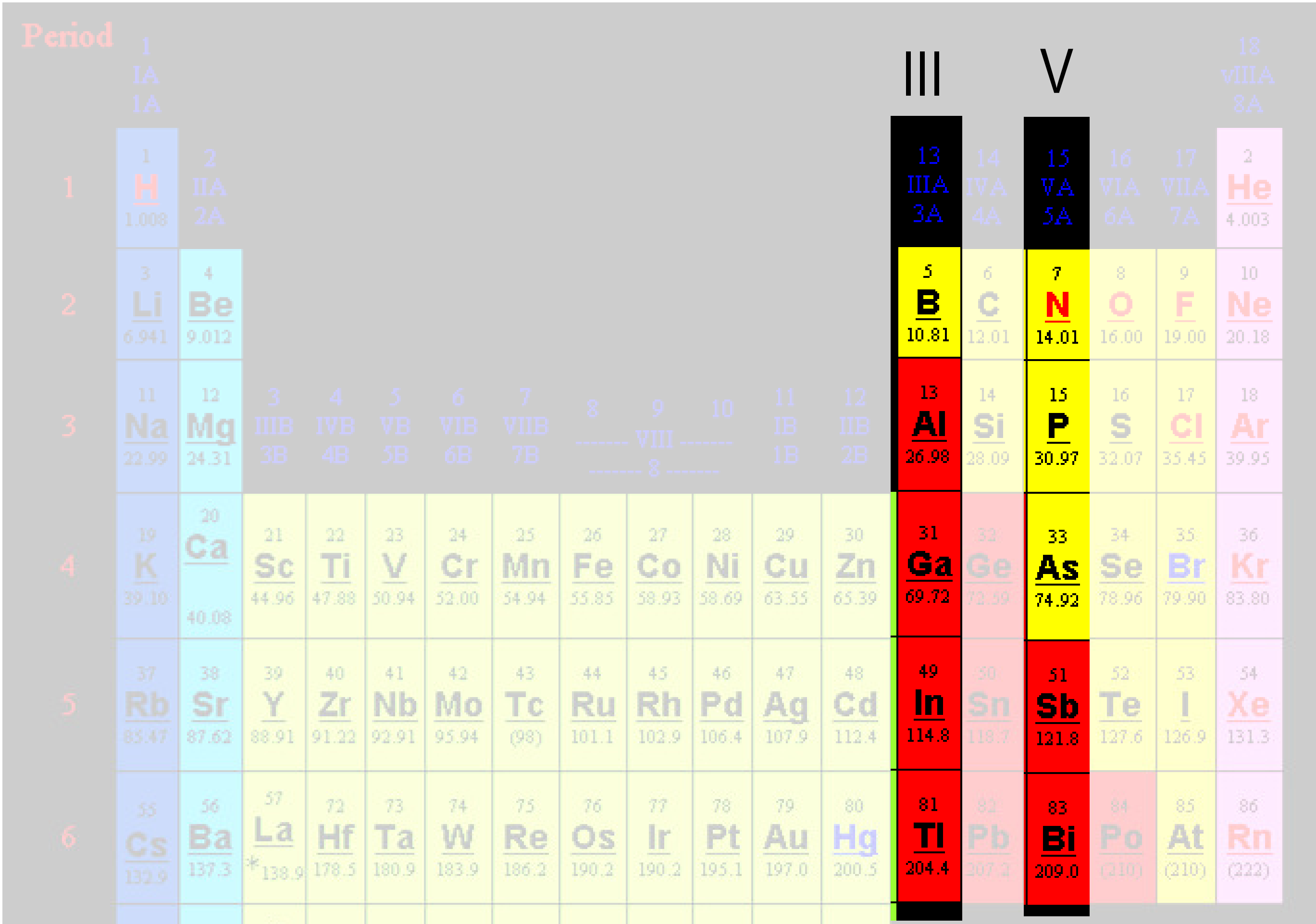
photon emission through e-h recombination

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



• compatibility with semiconductor substrates: Si, GaAs, InP

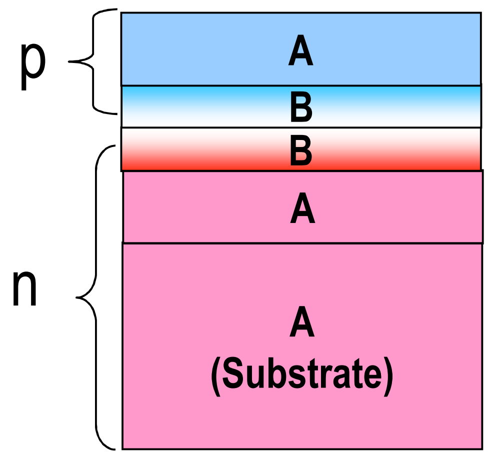
III-V semiconductor materials



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.

Semiconductor Heterostructures

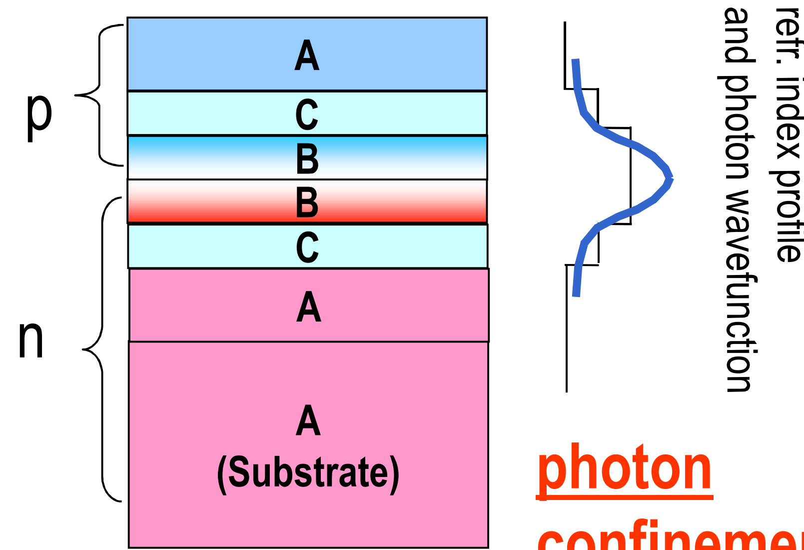
Double Heterostructure (DH)



e-h confinement

$E_g(A) > E_g(B)$

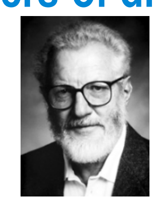
Separate Confinement Heterostructure (SCH)



photon confinement

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

Combination of layers of different crystalline semiconductors.

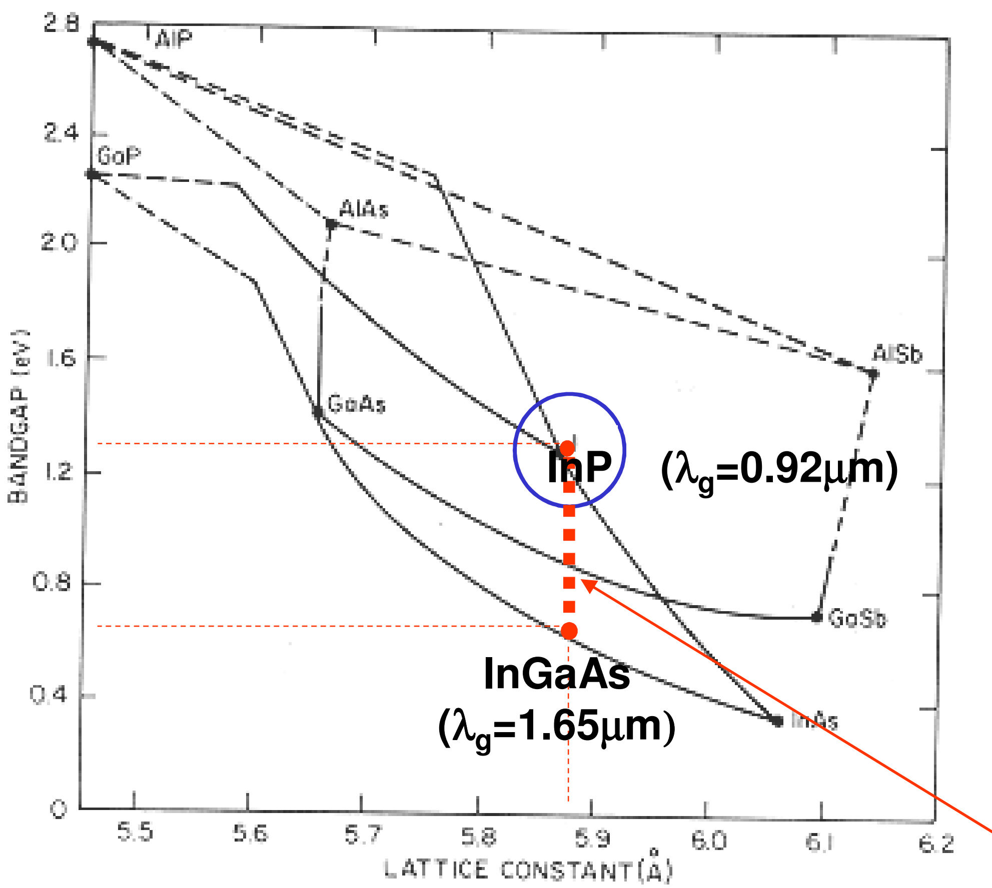


H. Kroemer, Varian associates 1963
(Nobel Prize in Physics, 2000)

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

Quaternary alloys InGaAsP / AlGaInAs

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



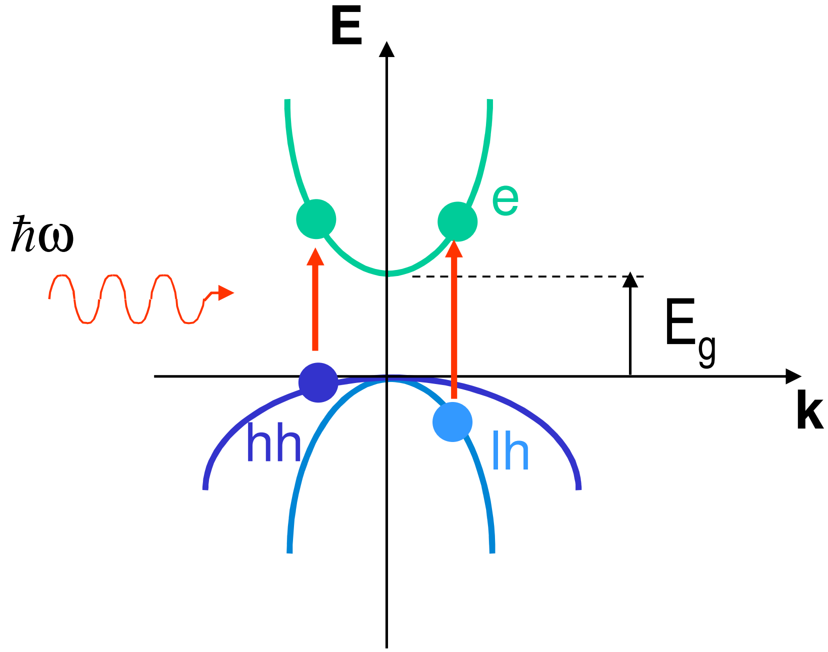
Variation of the bandgap as a function of lattice constant for III–V binary and alloy semiconductors

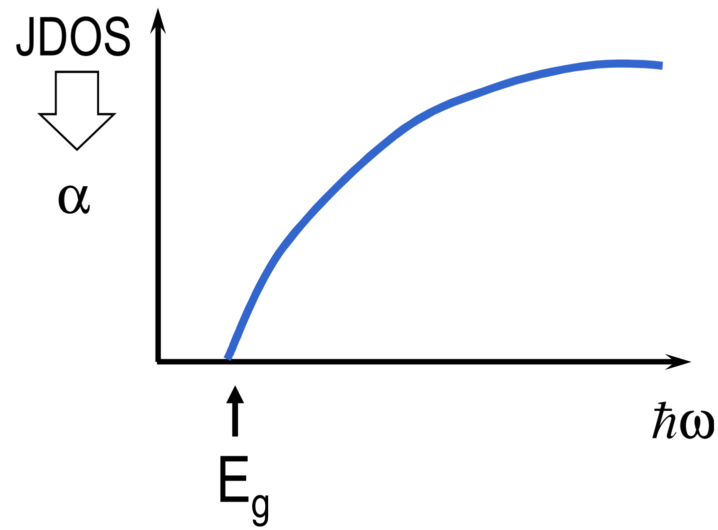
$In_{1-x}Ga_xAs_yP_{1-y}$ / $Al_{1-x-y}Ga_xIn_yAs$ alloys cover all the spectral range required for optical telecom

- 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)

(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

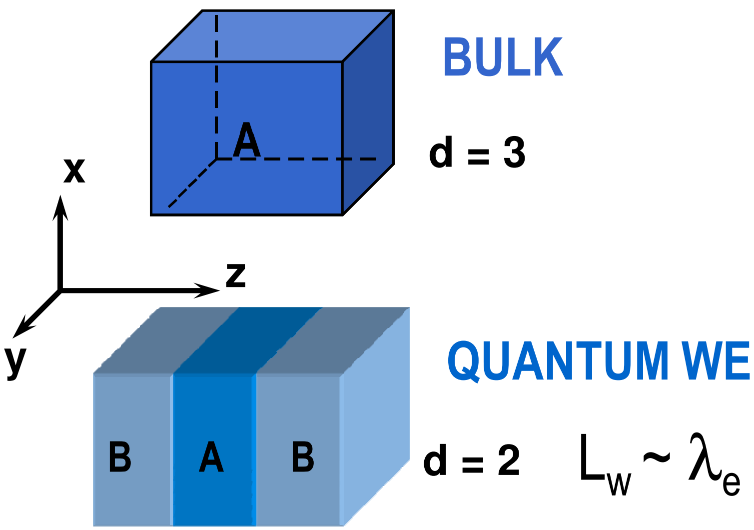
$$JDOS \propto \sqrt{\hbar\omega - E_g}$$

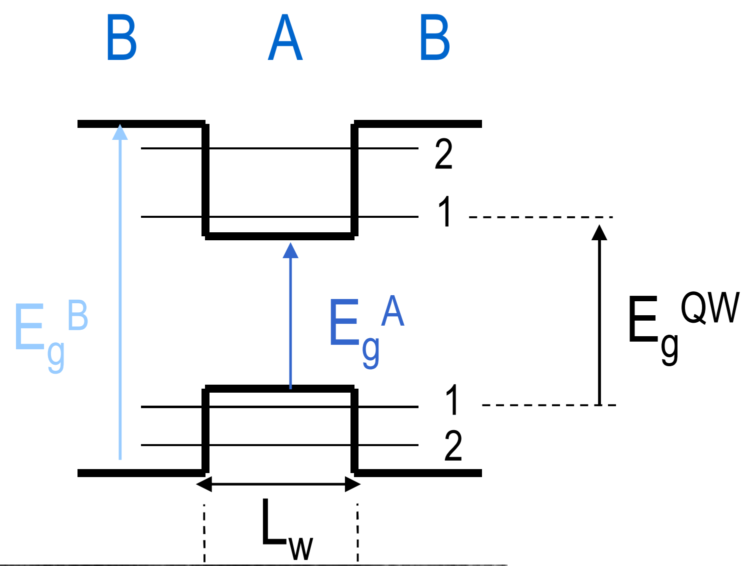
Quantum Wells

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

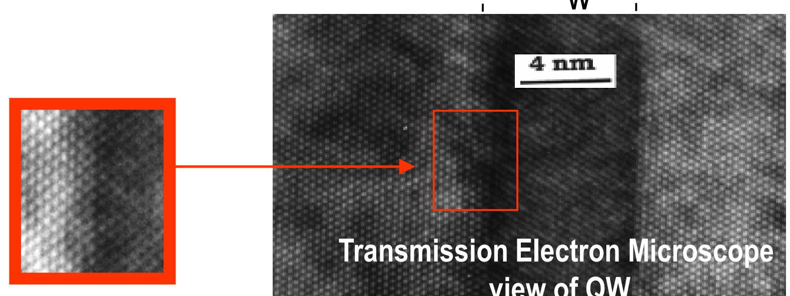
C. H. Henry, Bell Labs 1972

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



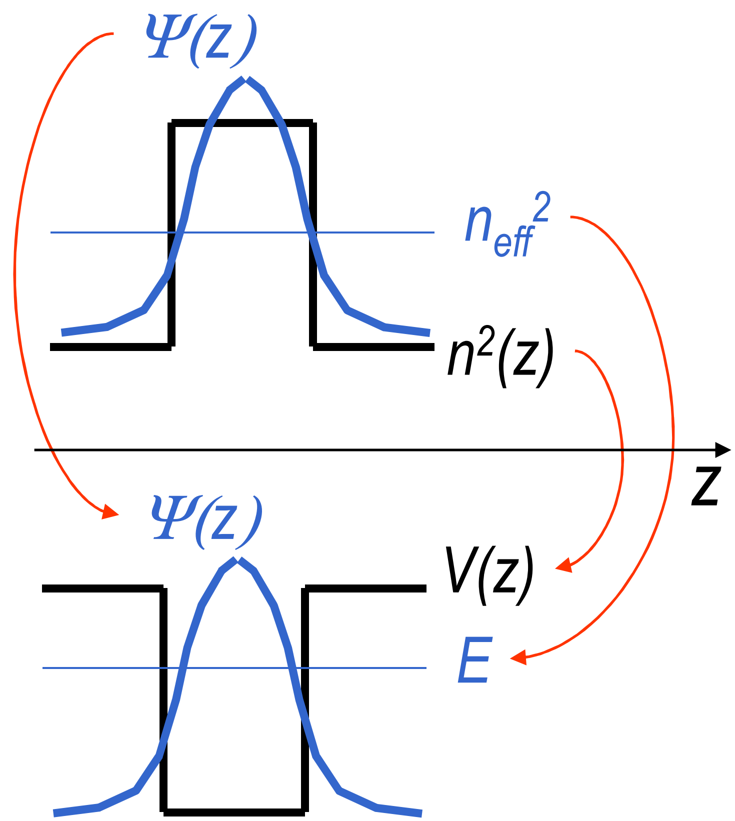
Photon wave eqn. vs. Electron wave eqn.

Helmholtz equation (*photon*)

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

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 $\Rightarrow$ barrier

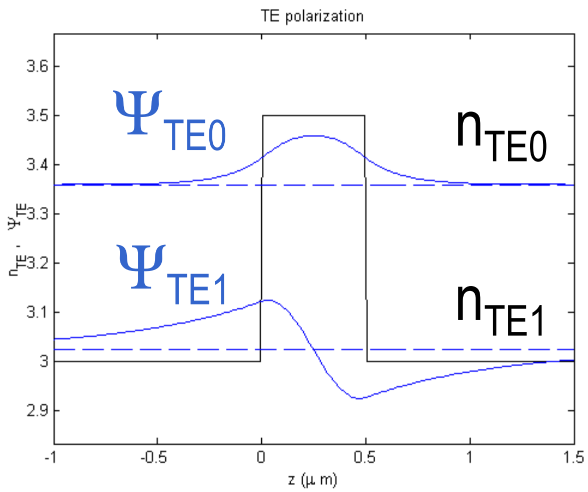
core $\Rightarrow$ well

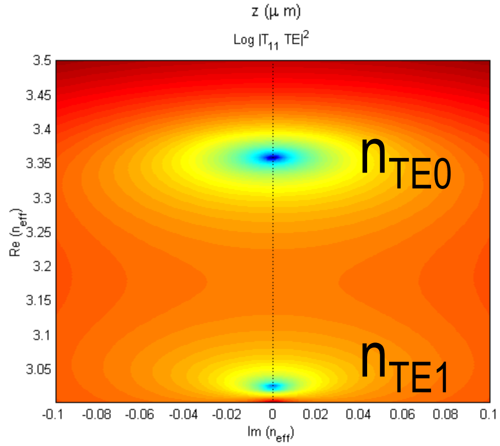
potential wells confine electrons (**quantum wells**)

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

Eigenfunction/Eigenvalues Calculation

Waveguide

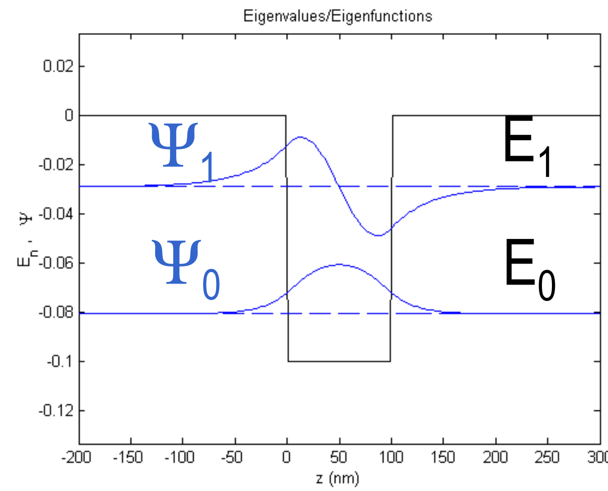


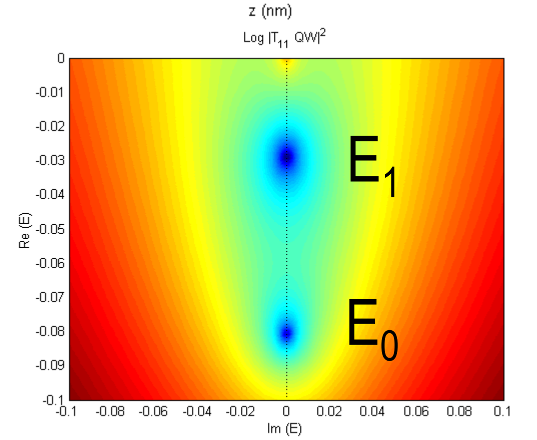


$$\Psi_{TE}(z^-) = \Psi_{TE}(z^+)$$

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

Quantum Well



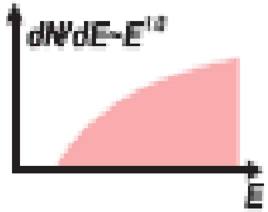


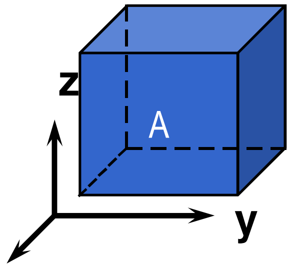
$$\Psi(z^-) = \Psi(z^+)$$

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

AVAGO TECHNOLOGIES

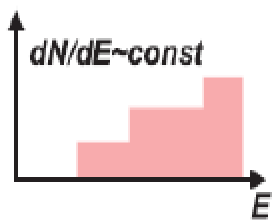
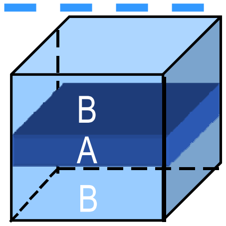
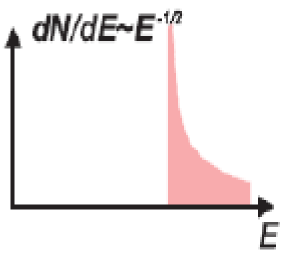
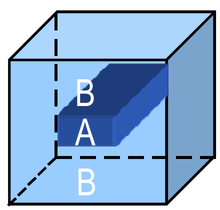
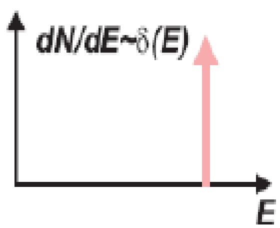
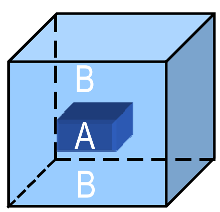
Reduced dimensionality structures





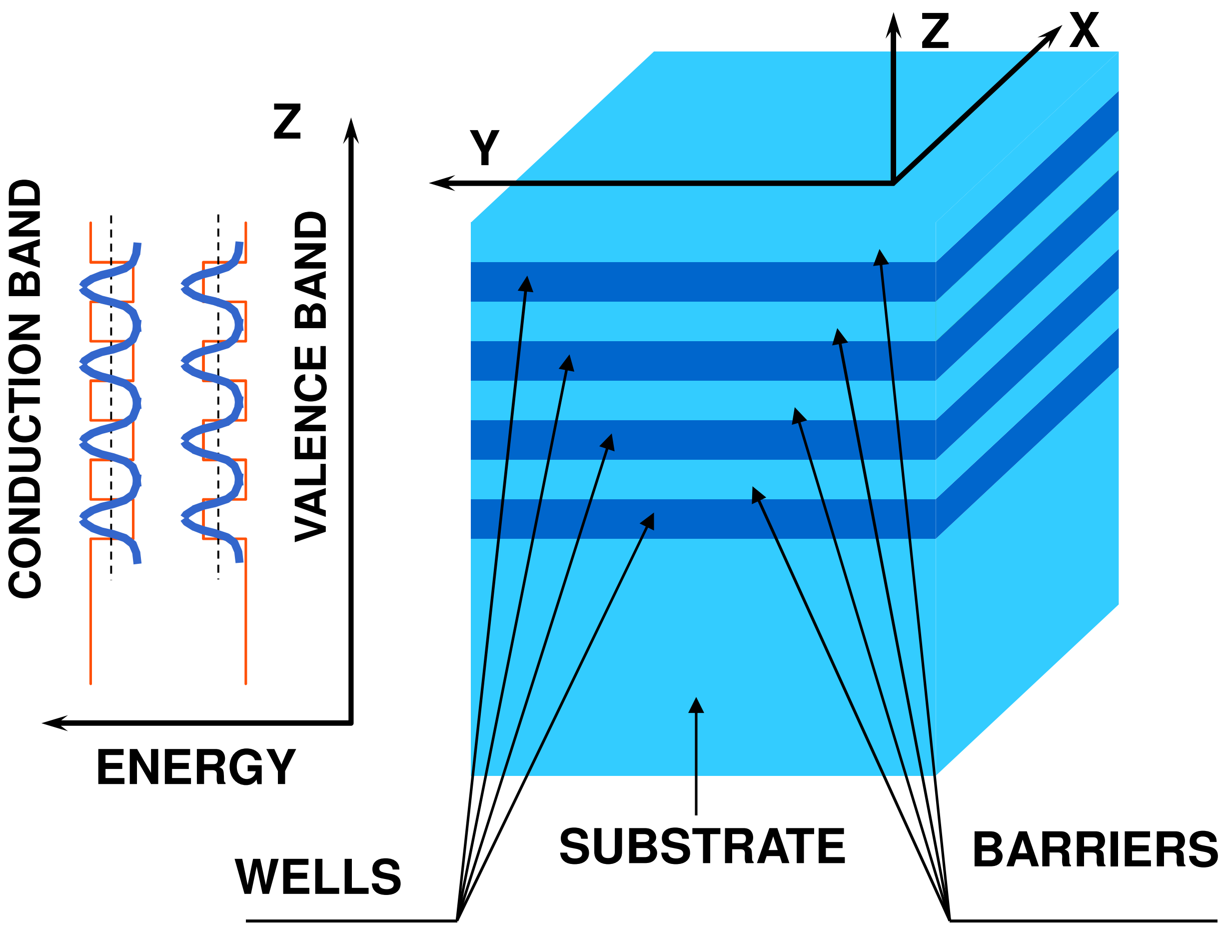
BULK

d = 3

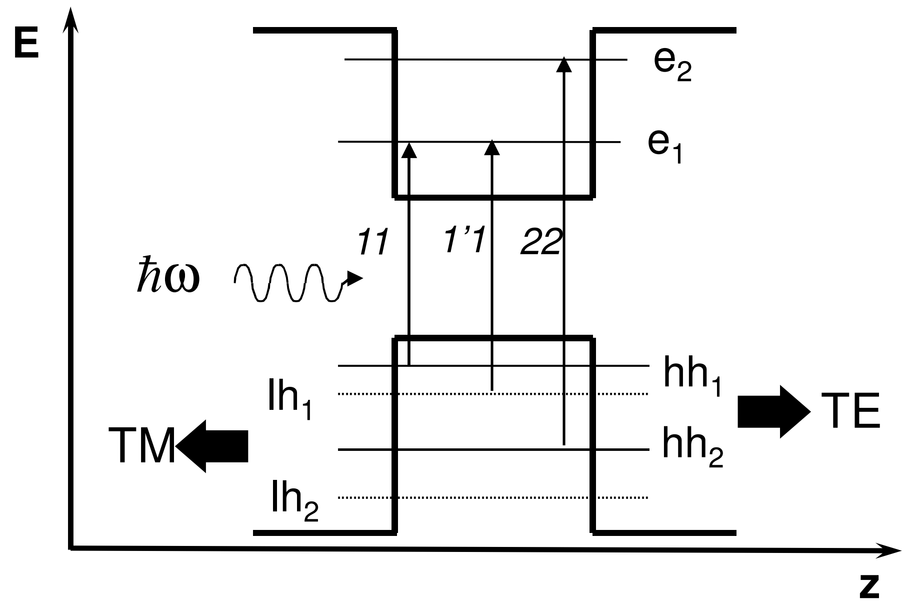
Q.M.		E.M.
  **QUANTUM WELL** **d = 2** $L_z \sim \lambda_e$	⟺	**PLANAR WAVEGUIDE** *1975: R.Dingle and C.Henry USA Patent Application*
  **QUANTUM WIRE** **d = 1** $L_z, L_y \sim \lambda_e$	⟺	**CHANNEL WAVEGUIDE**
  **QUANTUM DOT** **d = 0** $L_z, L_y, L_x \sim \lambda_e$	⟺	**OPTICAL RESONATOR**

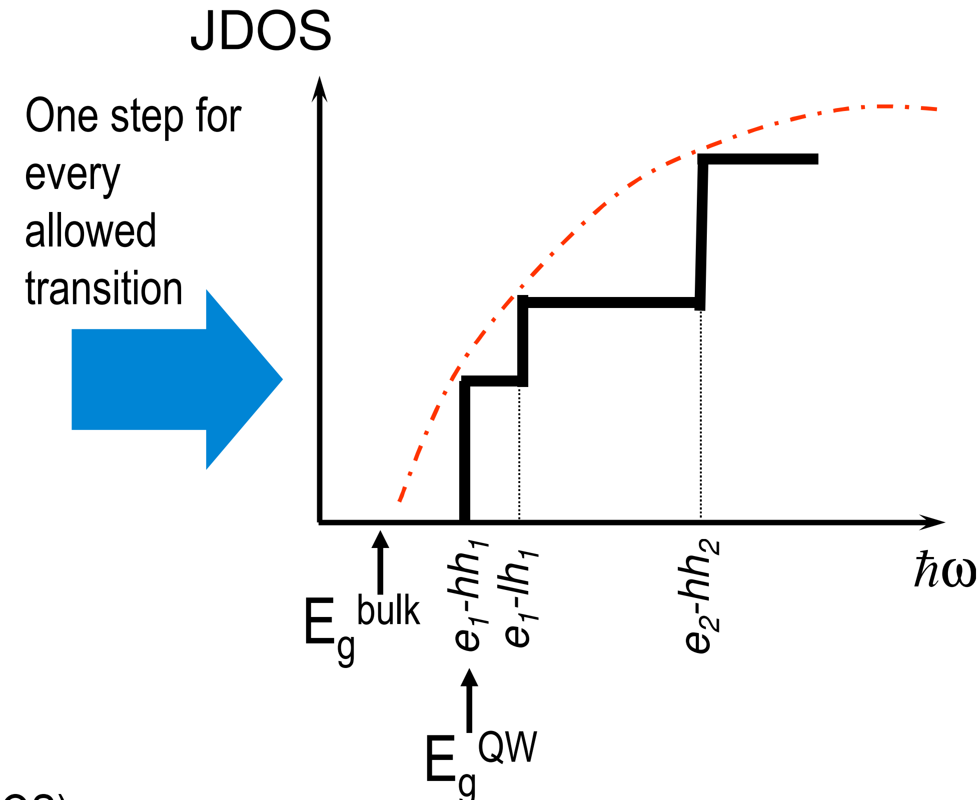
MQW heterostructures

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



QW band structure



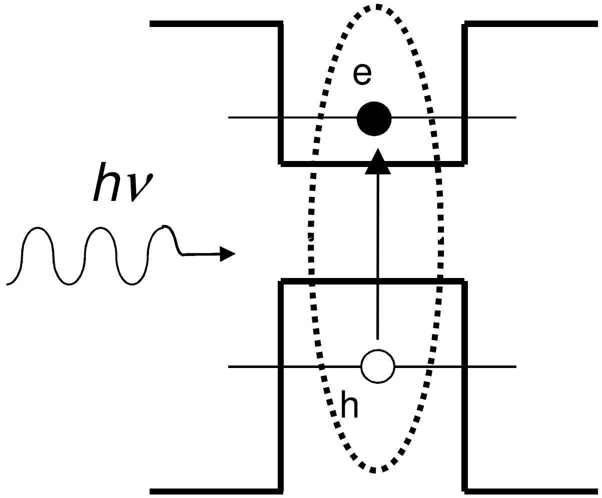


2D JDOS related features:

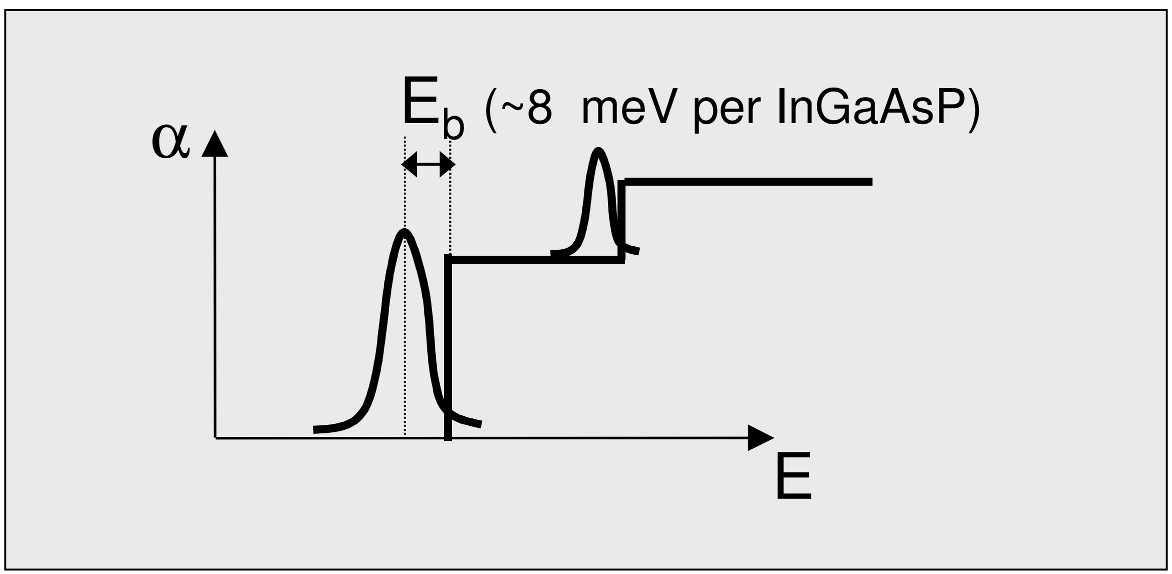
- Sharp absorption edge (2D JDOS)
- High differential gain
- Wide gain bandwith
- High electroabsorption efficiency (QCSE)
- Strong optical nonlinearities
- . . .

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

Excitons

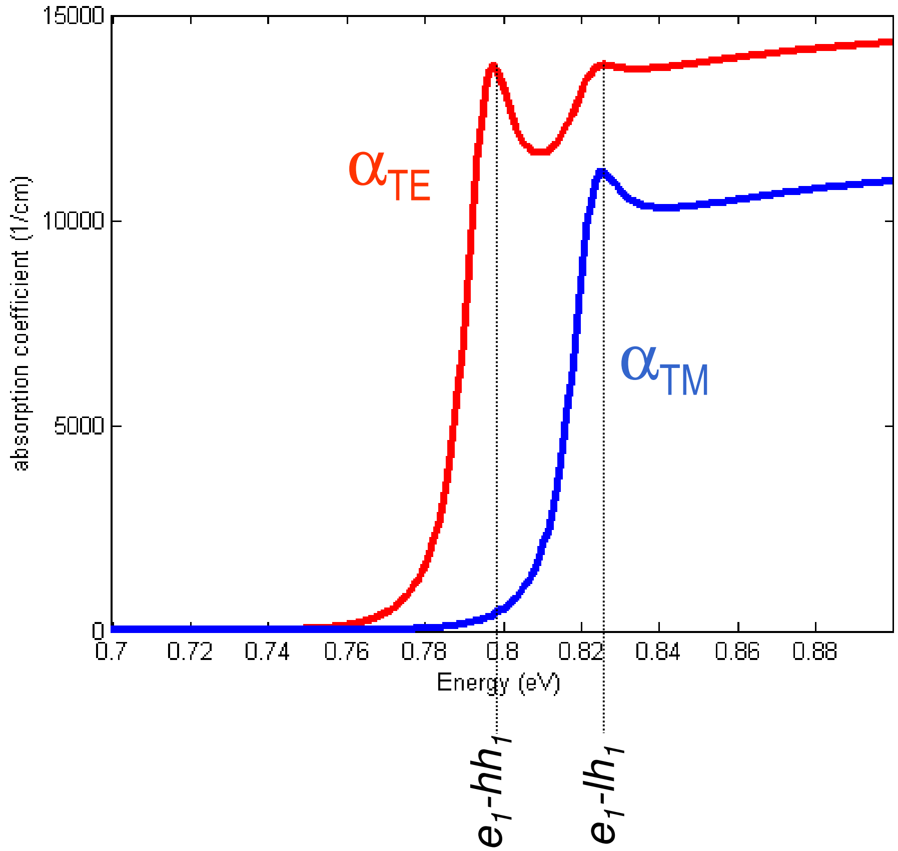


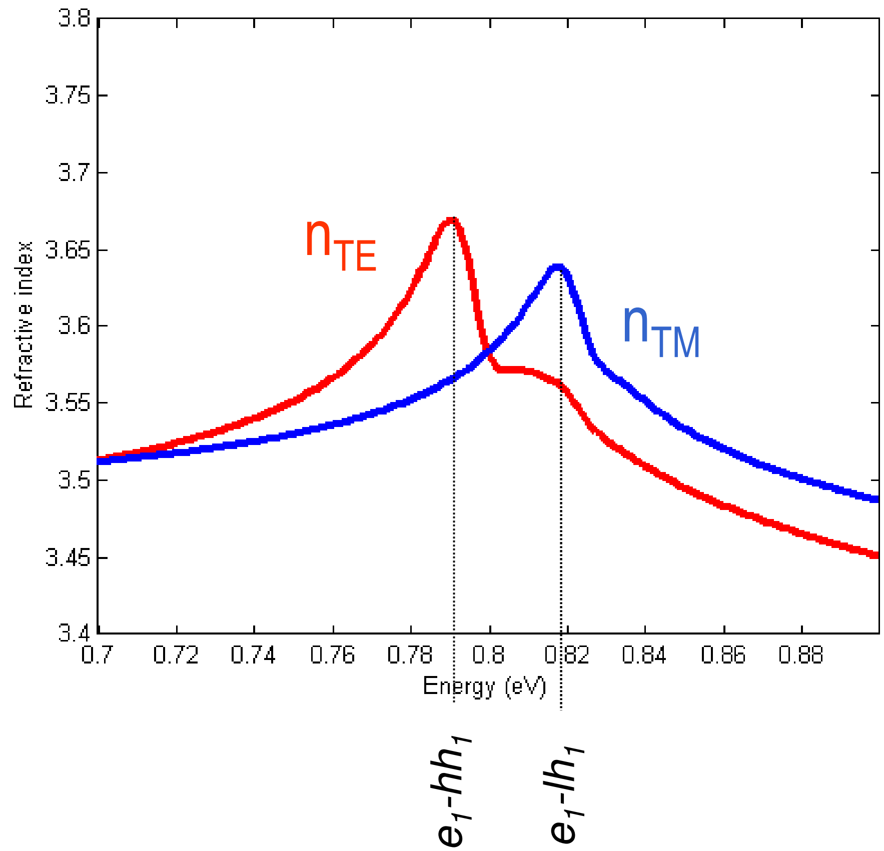
e - h semi-bound states ($\tau \sim$ 100 fs) which produce sharp absorption peaks detuned from the transition energies (absorption steps) by their binding energy



QW optical properties

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





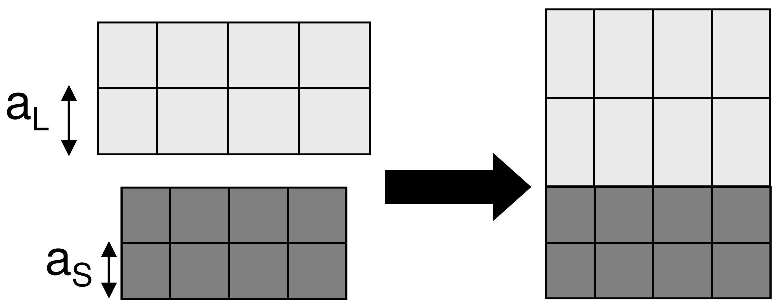
Strong dichroism ⇒

<u>Polarisation selection rules:</u>
TE: 3/4 hh, 1/4 lh
TM: 0 hh, 1 lh

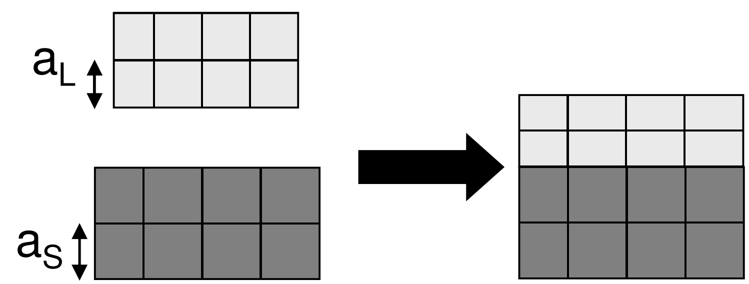
Strain(1)

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

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



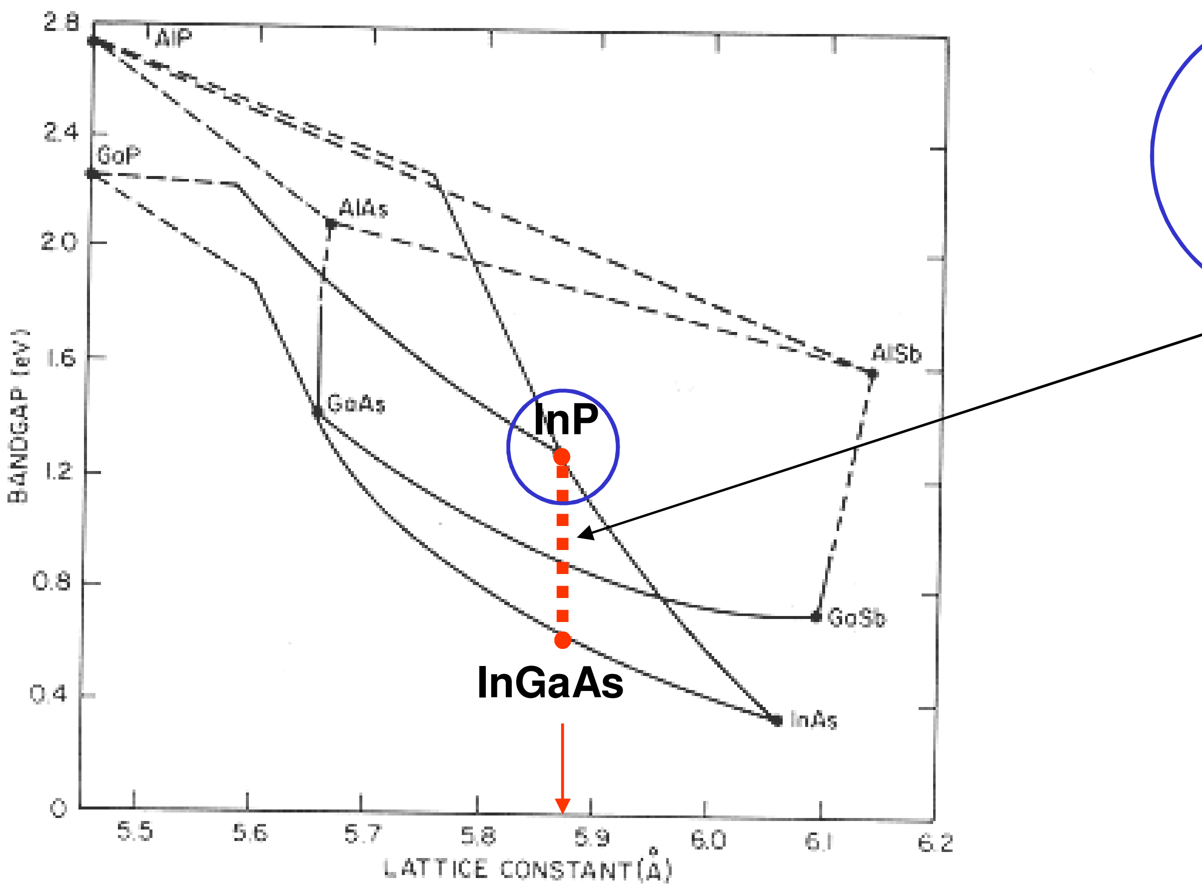
compressive strain
m>0



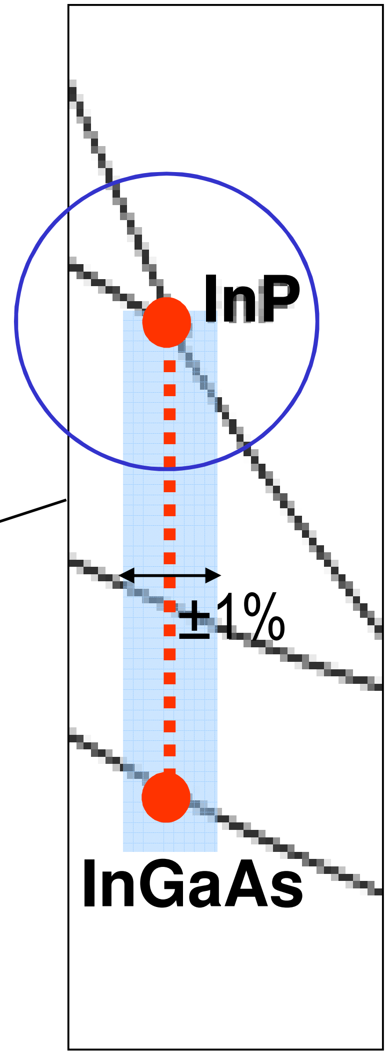
tensile strain
m<0

Strain(2)

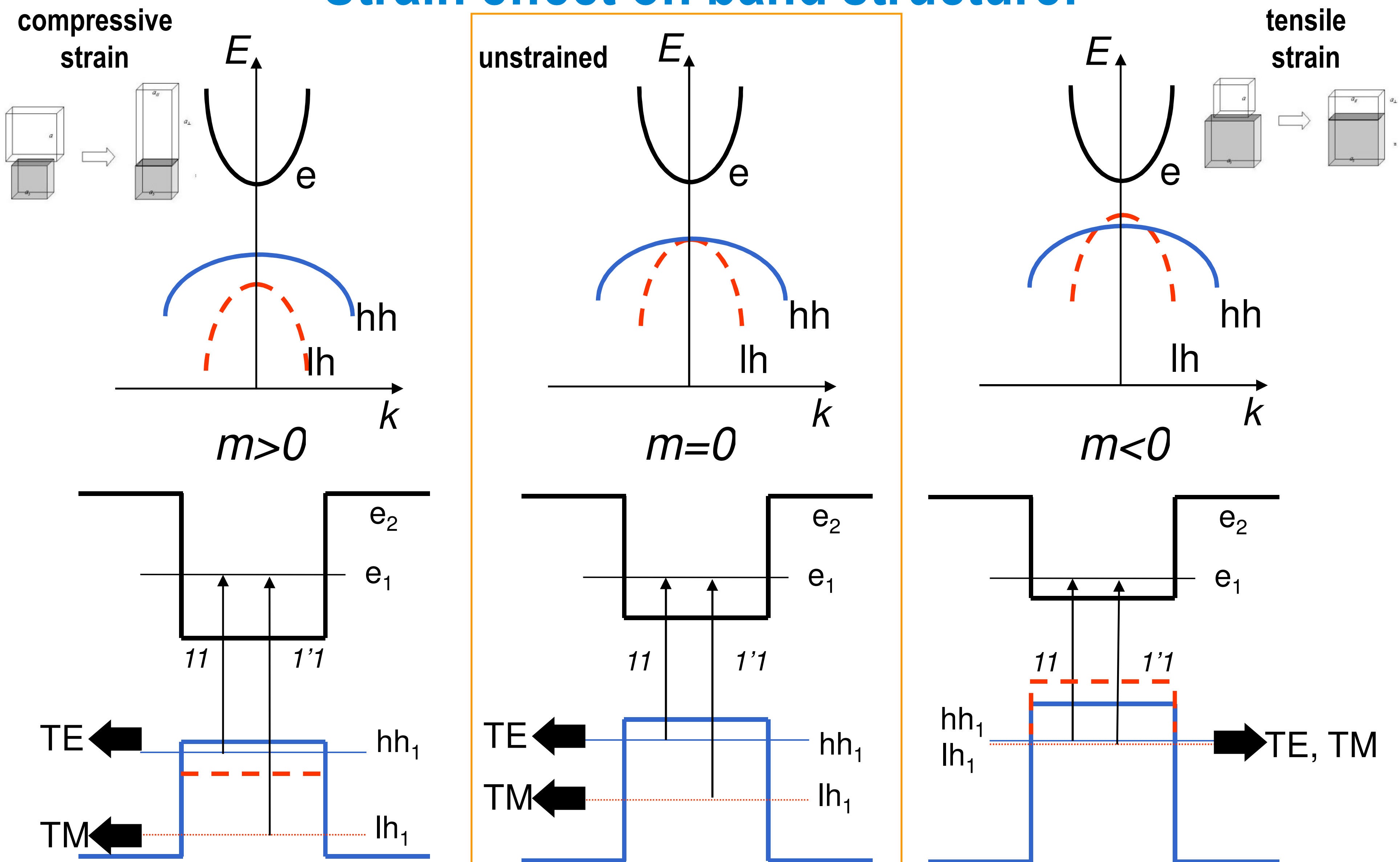
T. P. Pearsall, GaInAsP Alloy Semiconductors, Wiley (1982)



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



Strain effect on band structure:

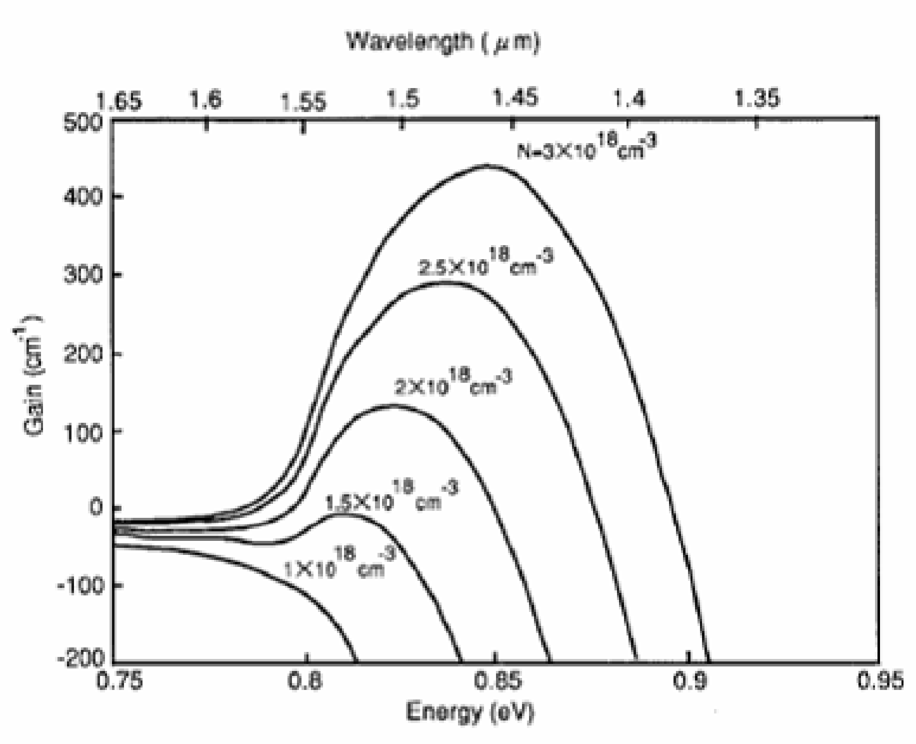


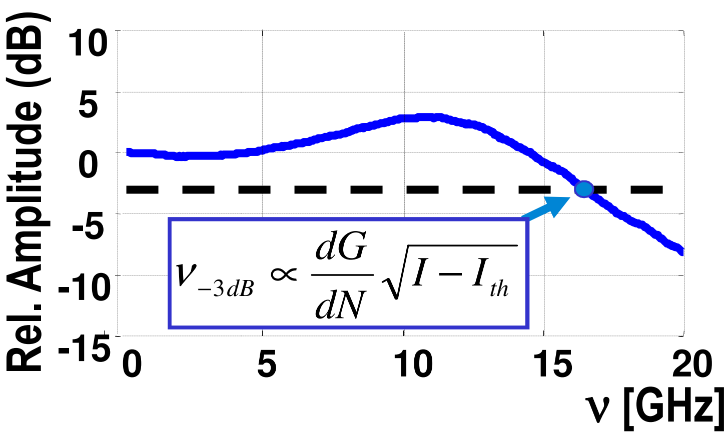
Low escape time
Fast devices
High To

Low dichroism
Polarization-independent devices

Optical gain in MQW vs. bulk

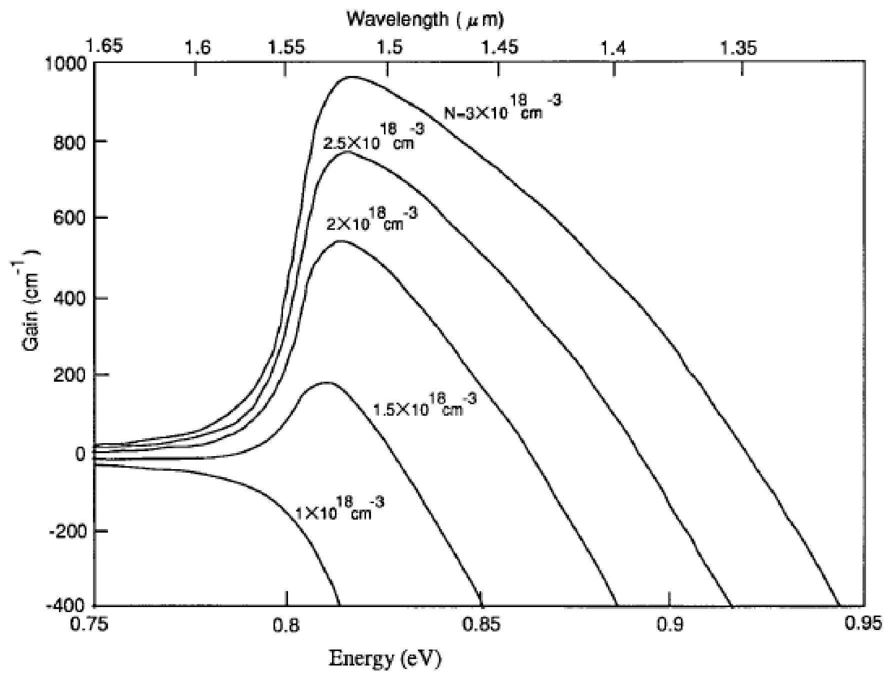
Bulk





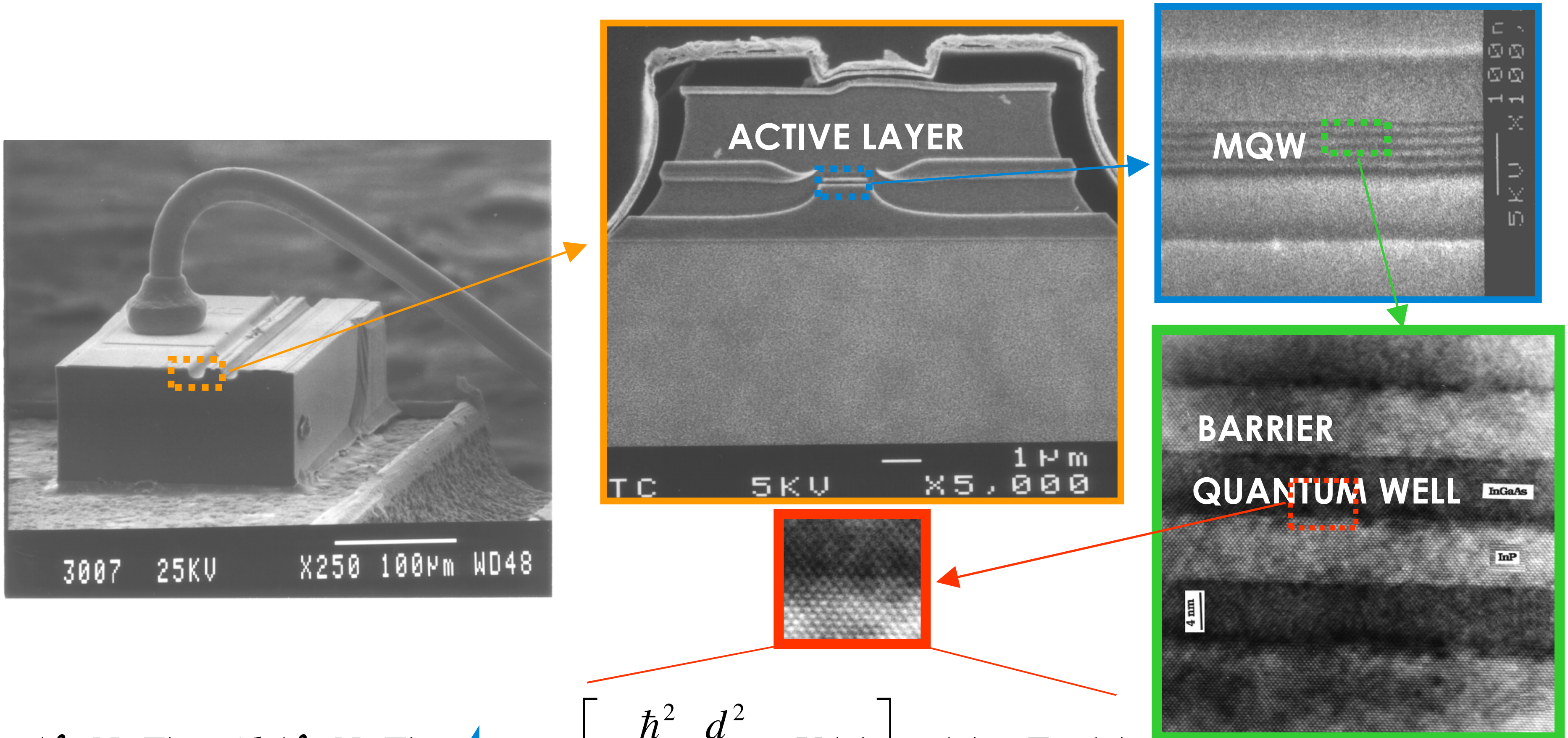
$$\nu_{-3dB} \propto \frac{dG}{dN}\sqrt{I - I_{th}}$$

MQW



- higher differential gain (dG/dN)
- wider spectral bandwidth

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 sub-monolayer manufacturing control (<u>$\sigma < 0.1$nm over 10cm^2</u>) achievable with MBE or MOCVD.

Avago's history

Former HP's semiconductor components division

1939

Hewlett Packard Foundation (T&M)

- Test & Measurement
- Life science
- Semiconductor components
- Computers/imaging…

November 1, 1999

Agilent spin-off

~40000 employees
T&M, Life science,
semiconductor components

Agilent Technologies

December 1, 2005

Avago spin off

~ 6500 employees
Semiconductor components

AVAGO TECHNOLOGIES

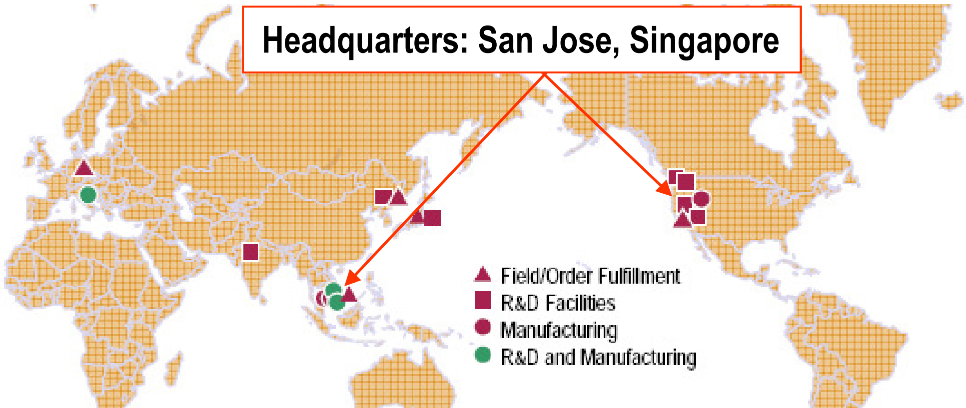
Agilent Technologies

T&M, Life science

~80000 employees
Computers, printers, imaging, …

Acquisition of TTC (Torino Technology Center)
former optoelectronic technology division of CSELT
R&D Corporate Center of STET (now Telecom Italia)

Product leadership in target markets



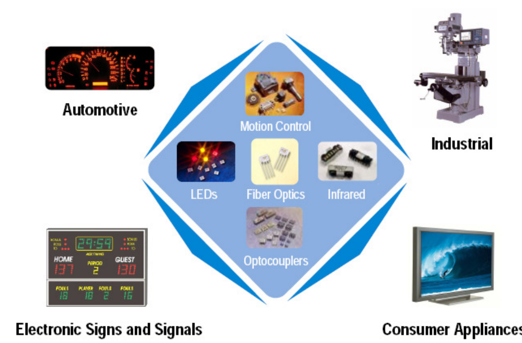
6500 products, more than 5000 patents

		Market Position
Optoelectronics and RF	•Optical Navigation	▪ #1 in optical mouse sensors
	•Isolation	▪ #1 in photo-IC optocouplers
	•Motion Control	▪ #1 in office automation encoders
	•Infrared	▪ #1 in infrared transceivers
	•LEDs and Displays	▪ #3 in LEDs
	•Wireless	▪ #1 in semiconductor-based filters
Enterprise Solutions	•Fiber Optics	▪ #2 in Fiber Optic Components
	•Imaging	▪ #2 in printer ASICs
	•Enterprise ASICs	▪ Leading supplier to Cisco and HP

Solutions for Mobile Handsets

Solutions for Storage, Computing and Networking

Solutions for Consumer, Industrial and Automotive

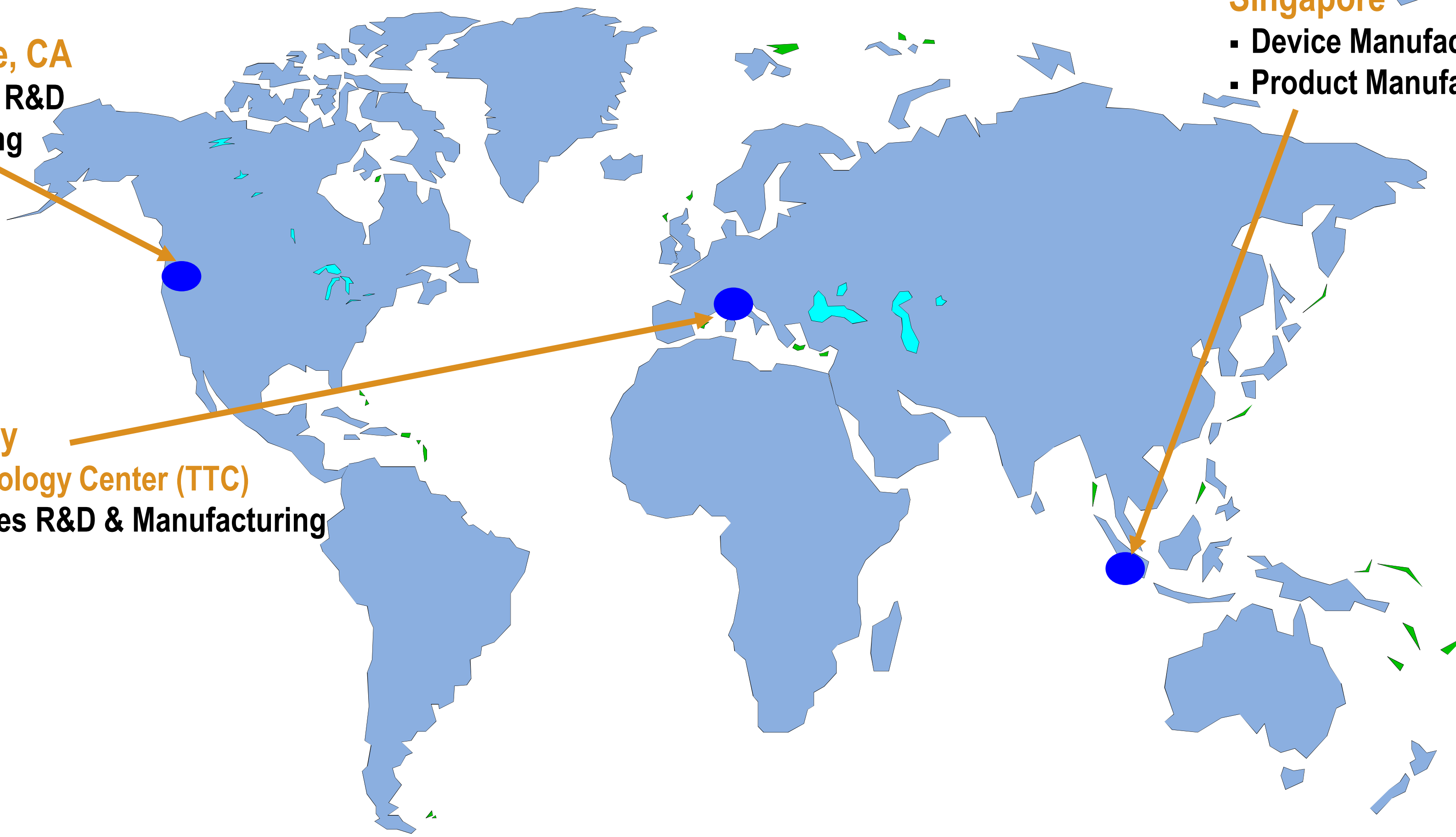


Fiber Optic Business

Worldwide Operations

Singapore
- Device Manufacturing
- Product Manufacturing

San Jose, CA
- Product R&D
- Marketing



Torino, Italy
Turin Technology Center (TTC)
- III-V Devices R&D & Manufacturing

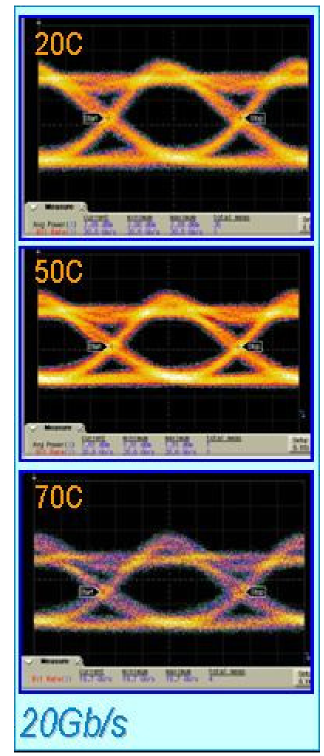
TTC current main activities

- **Manufacturing of 10Gb/s FP and DFB lasers**
  (>900k laser chips fabricated and delivered since 2007)

- **R&D on high bandwidth uncooled DFB lasers**

- **R&D on semiconductor technology**

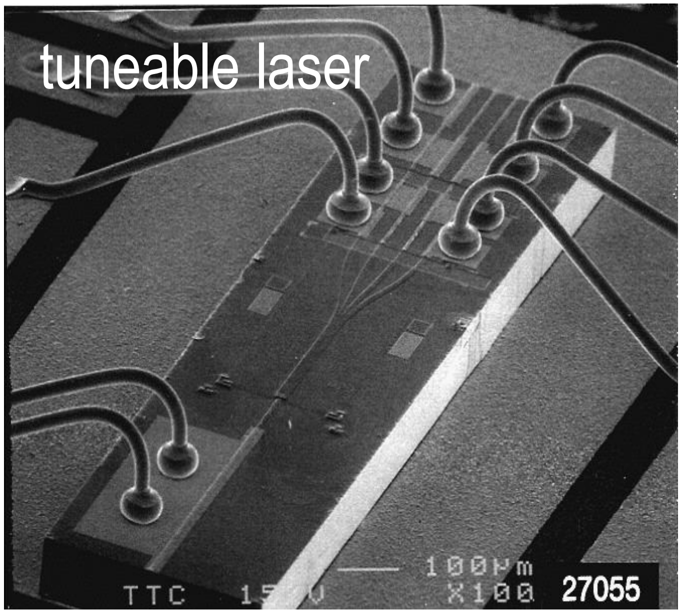
R&D on photonic devices since late 70's

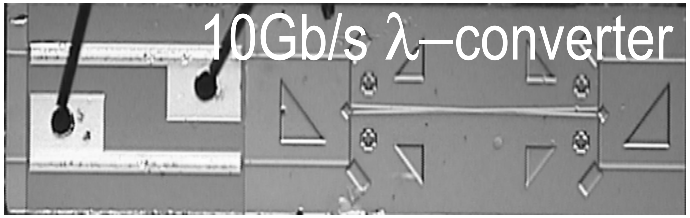


AVAGO TECHNOLOGIES

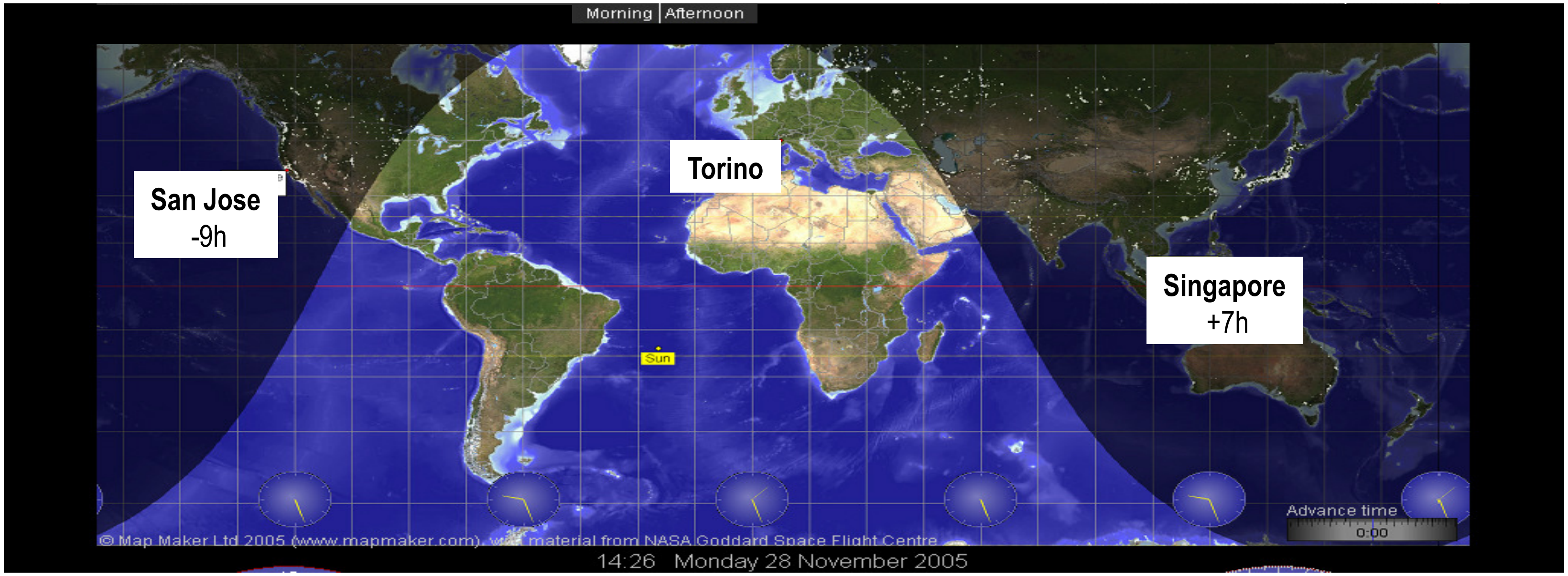
TTC activity in photonics devices since late 70's

- Lasers: FP, DFB, DBR, EML, WDM tuneable
- Detectors: PIN, APD
- SOA: gain blocks, clamped-gain, XGM and XPM
- Modulators
- All-optical (nonlinear) photonic devices
- Wavelength converters
- …





Laser fabrication requires team work across the globe: not an easy task!



BOOKS:

- *L. A. Coldren, S. W. Corzine,* **Diode Lasers and Photonic Integrated Circuits**
  Wiley Series in Microwave and Optical Engineering

- *G. Ghione,* **Semiconductor Devices for High-Speed Optoelectronics**
  Cambridge University Press

LINKS:
- **http://www.lightwaveonline.com**
- **http://www.photonics.com/**
- **http://www.avagotech.com/**

claudio.coriasso@avagotech.com

Thanks for your attention