High Power Semiconductor Lasers

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Torino Diode Fab

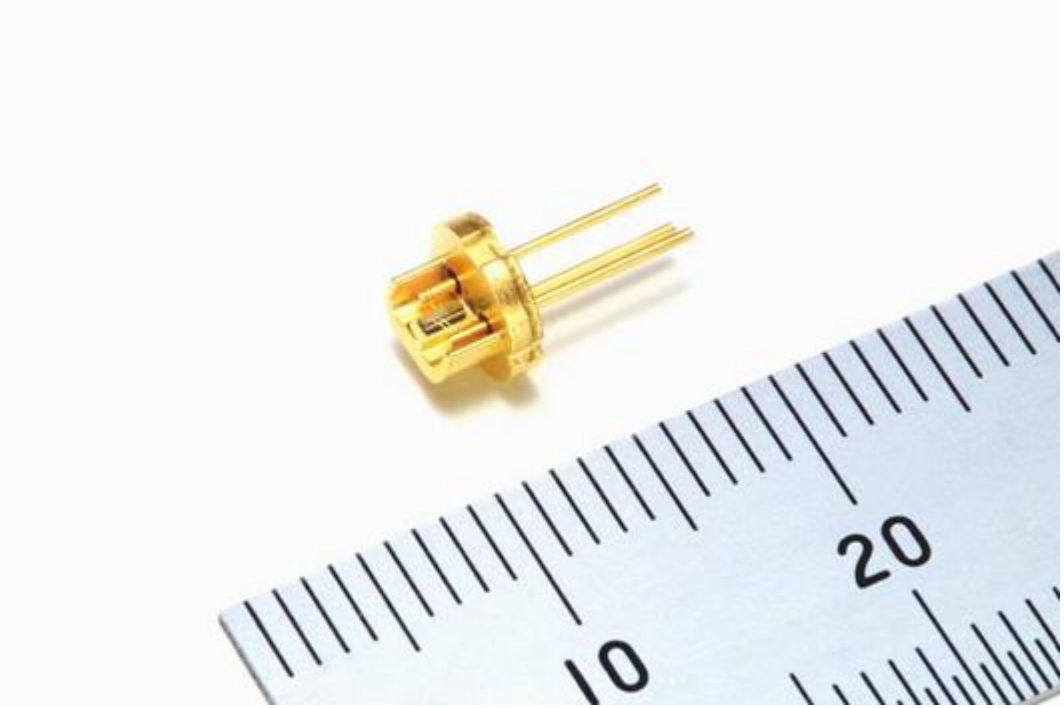
www.primaelectro.com

Prima Electro

Outline

1) Introduction
2) Applications
    - Optical Communication
    - Industrial Processing
3) Operation principle and key points
4) Prima Electro snapshot

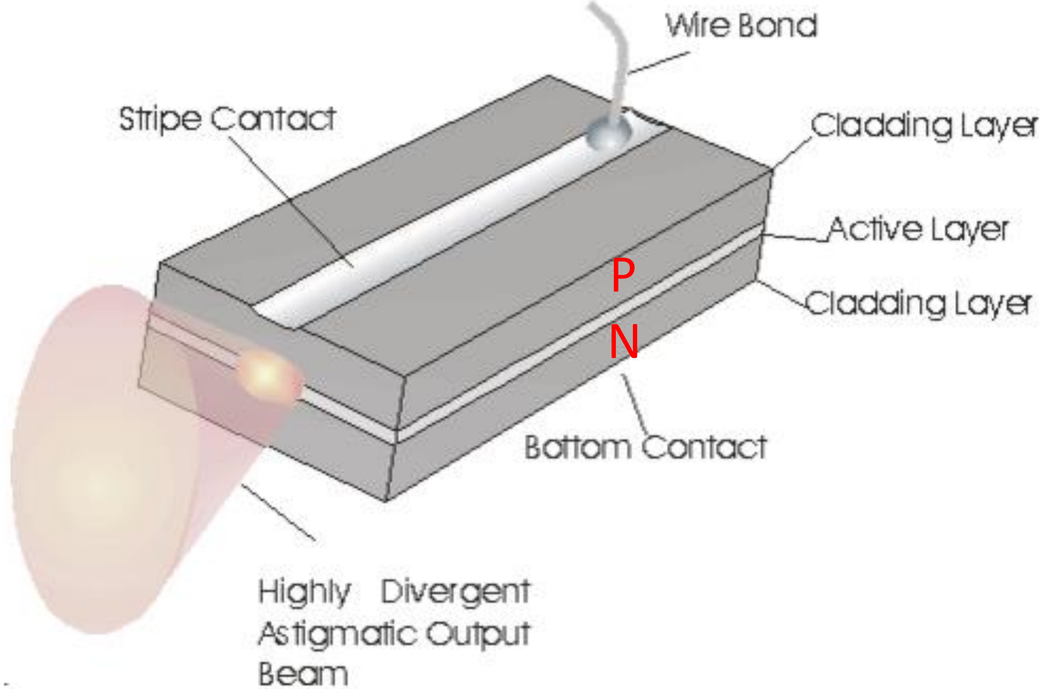
Semiconductor Laser Introduction



Semiconductor laser or Laser Diode

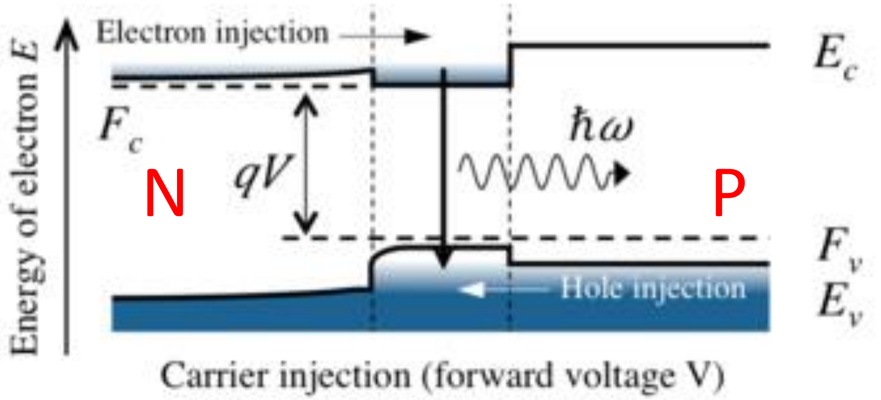
- ☐ A laser diode is an electrically pumped semiconductor hetero structure in which the active medium is embedded within a P-N junction

- ☐ Optical gain is provided by the radiative recombination of electrons and holes in a direct band gap semiconductor active layer



P-N junction

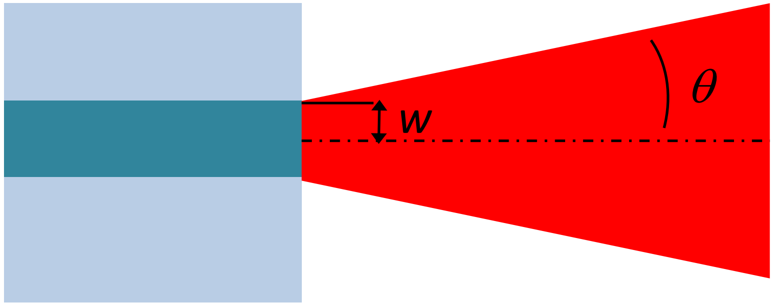
- ❑ When the P-N junction is forward-biased, electrons are injected from the N side while holes are injected from the P side. Both electrons and holes are confined within a lower bandgap region (which can be so small to allow quantum confinement) where they recombine via stimulated emission excited by an existing photon
- ❑ Diode Lasers can be extremely efficient showing “wall plug efficiency” (ratio between optical power and electrical power) exceeding 70%



Beam Quality

The Beam Parameter Product (BPP) quantifies the quality of a laser beam and how well it can be focused to a small spot. It is the product of a laser beam's far-field divergence angle (half-angle) and the radius of the beam at its narrowest point (the beam waist).

$$BPP = w \times \vartheta \ [mm\, mrad]$$



$$BPP_{Gaussian} = \frac{\lambda}{\pi}$$

$$\frac{BPP}{BPP_{Gaussian}} = M^2 \geq 1$$

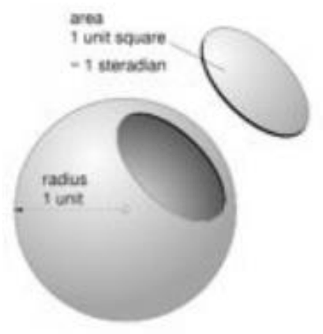
BPP cannot be reduced by manipulating the optical beam with linear optics (lenses, mirrors, …)

Combination of optical beams implies adding their BPPs

Brightness or Radiance

Federal Standard 1037C

Telecommunications: Glossary of Telecommunication Terms



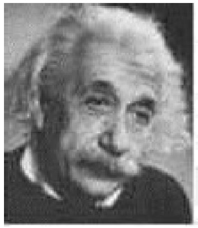
Radiance: Radiant power, in a given direction, per unit solid angle per unit of projected area of the source, as viewed from the given direction.

$$B = \frac{P}{\pi w^2 \pi \vartheta^2} = \frac{P}{\pi^2 BPP^2} \quad [W cm^{-2}\ sterad^{-2}]$$

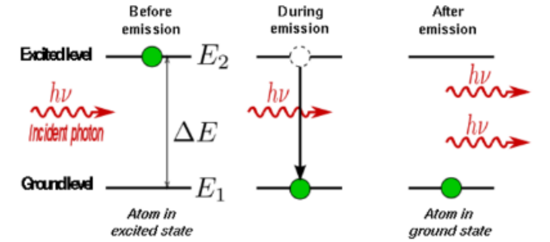
for a Gaussian beam: $$B = \frac{P}{\lambda^2}$$

Material processing efficiency is proportional to laser brightness

LASER history



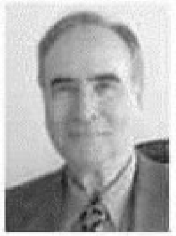
1917, A.Einstein
"Zur Quantentheorie der Strahlung" Physik Annalen



$$E_2 - E_1 = \Delta E = h\nu$$

1958, A.Schawlow, C.Townes (Bell Labs)
"Infrared and Optical Masers"
Physical Review

Maser = Microwave Amplification by Stimulated Emission of Radiation



1960, T.Maiman (1927-2007) (Hughes Research Labs)
"Stimulated Optical Radiation in Ruby" Nature

Laser = Light Amplification by Stimulated Emission of Radiation

A brilliant solution in search of a problem!

Semiconductor Laser:

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

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

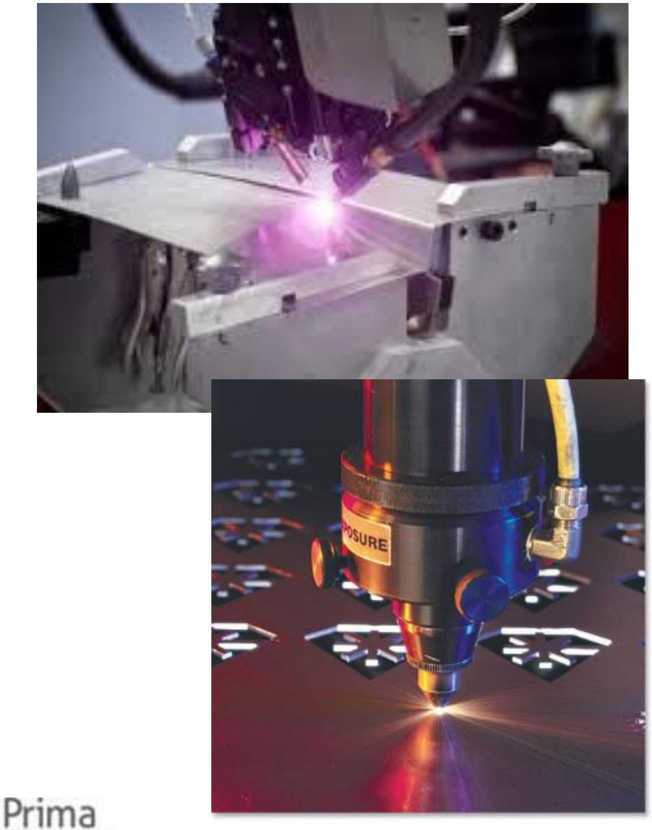
1970: First Realization of Heterostructure Semiconductor Laser (Z. Alferov)

1972: Invention of Quantum Well (Bell Labs)

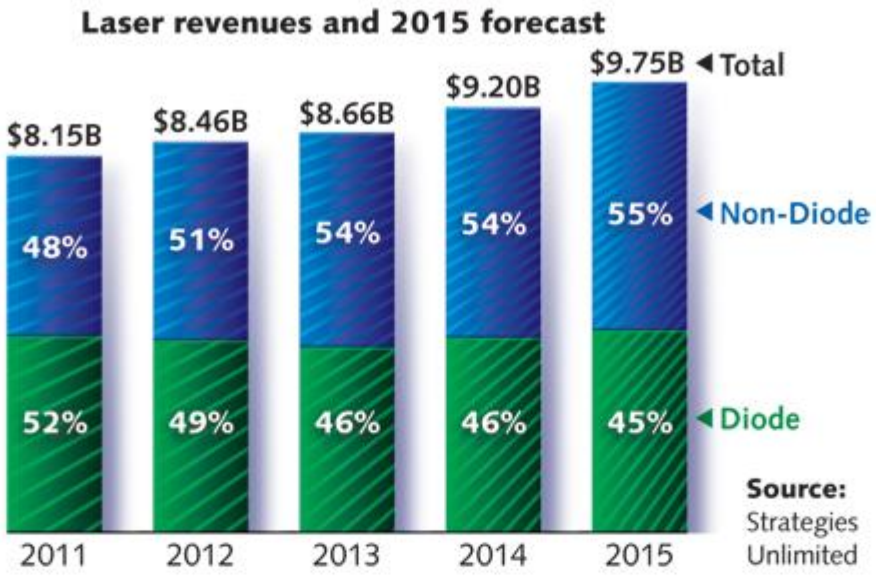
1984: First Realization of Strained MQW in semiconductor laser

Z. Alferov receiving
his Nobel Prize
Stockholm 2000

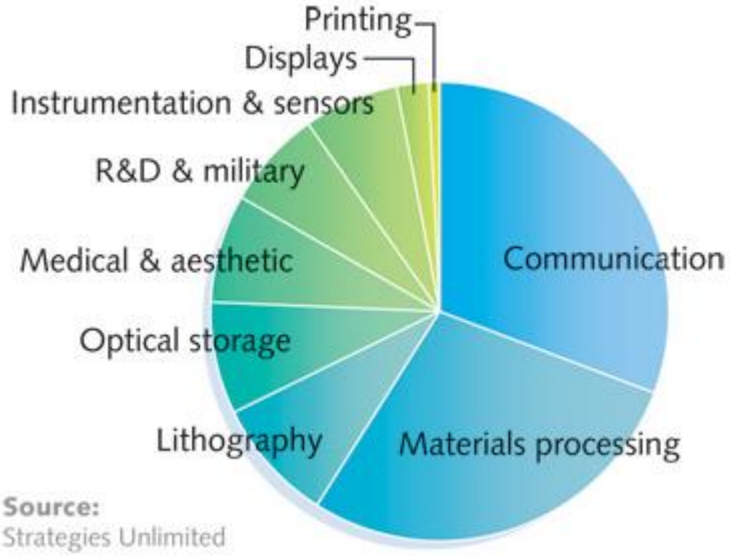
Semiconductor Laser Applications



Laser Diode Market



Source: Strategies Unlimited



Source: Strategies Unlimited

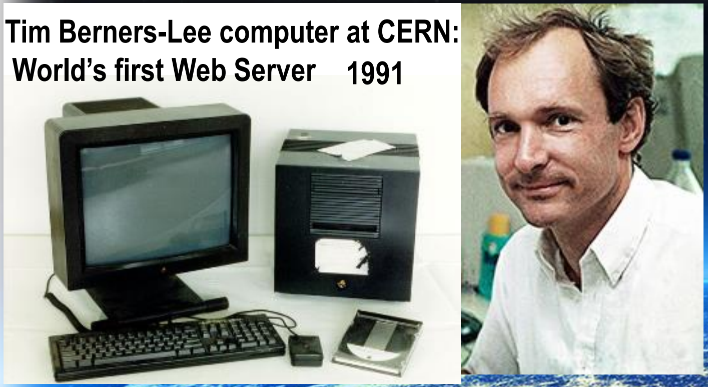
The total laser diode market is expected to reach USD 11.94 Billion by 2020, at a CAGR of 13.0% between 2015 and 2020

http://www.marketsandmarkets.com/

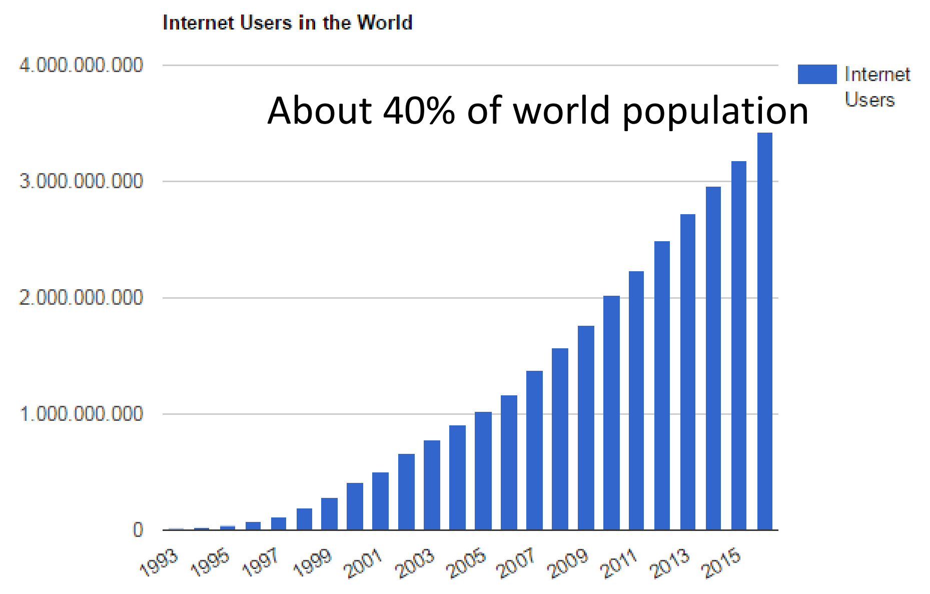
Communication Growth

Communication has always been one of the main driving force for the development of new technologies:

Telegraph, Telephone, Fiber Optic, Laser, …



Tim Berners-Lee computer at CERN: World's first Web Server 1991

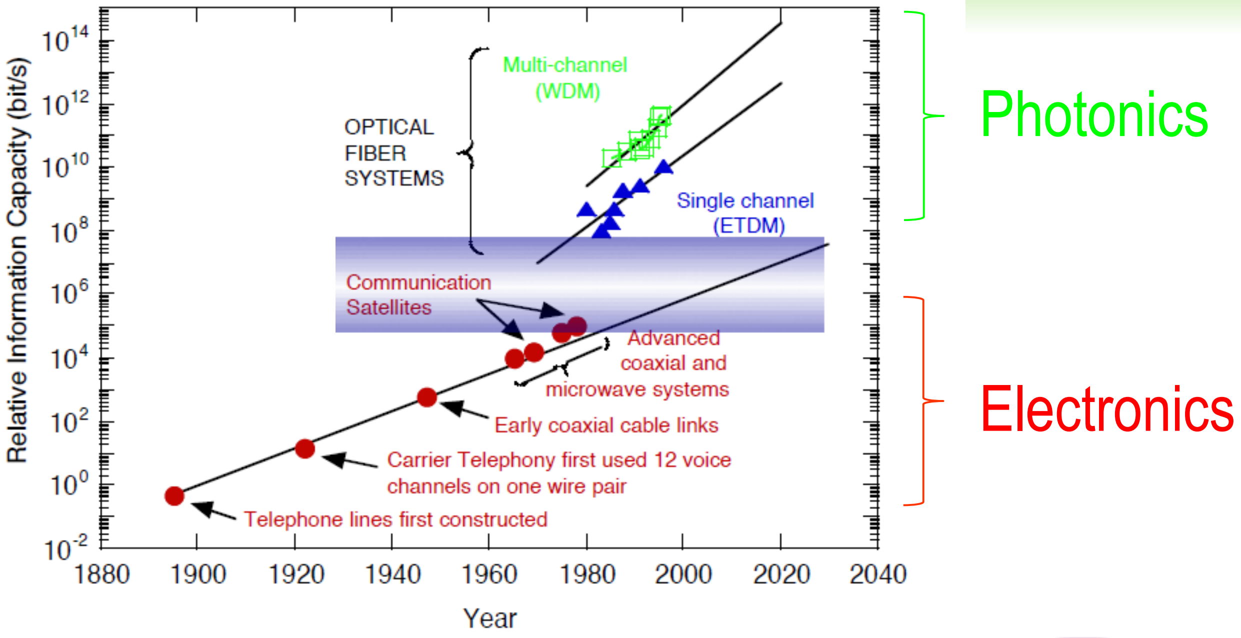


Internet Users in the World

About 40% of world population

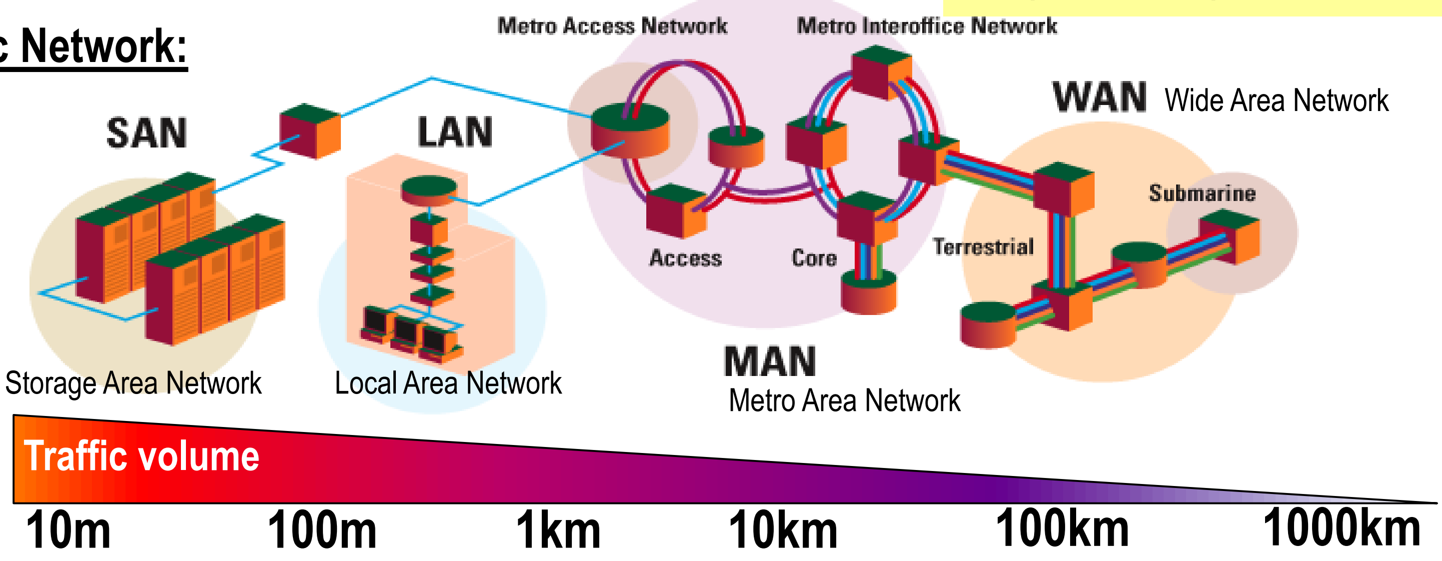
Worldwide communication traffic is doubling every 18 months (2dB/year)

Laser Diode in Optical Communication



- **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)**

Today Photonic Network:

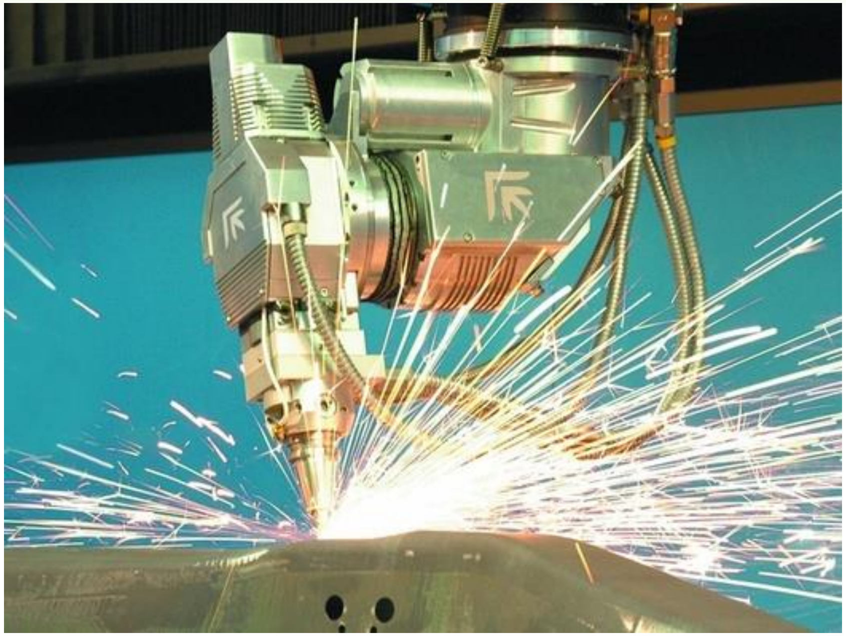


Material Processing

- Laser welding
- Laser cutting
- Laser drilling
- Laser hardening
- Laser microprocessing

Subtractive manufacturing

- Additive manufacturing

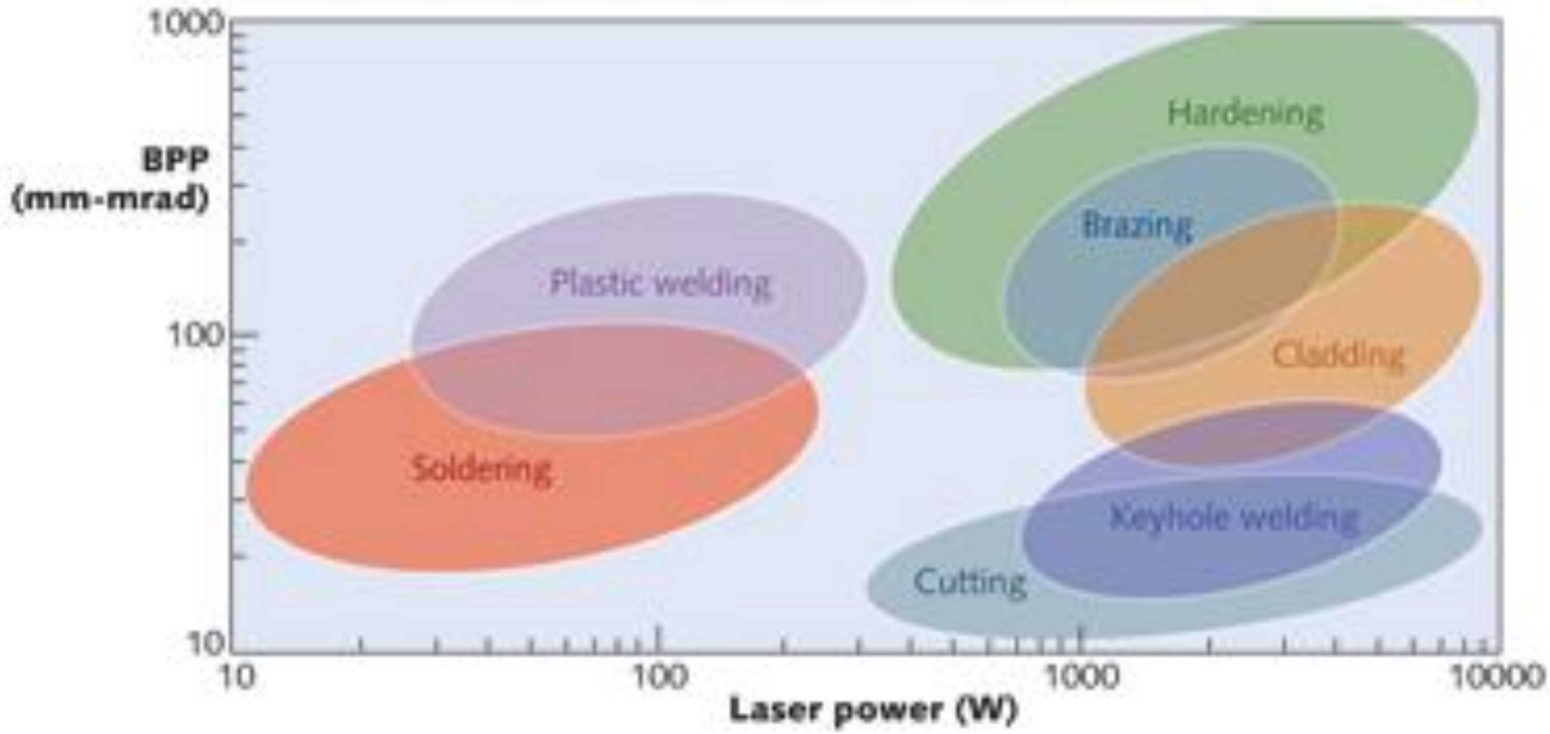


Material processing efficiency is proportional to Laser Brightness:

- **High Power**
- **High Beam Quality (Low BPP)**

$$B = \frac{P}{\pi^2 BPP^2}$$

BPP required for material processing



Additive Manufacturing or 3D printing

- A process by which digital 3D design data is used to build up a component in layers by depositing material

- Advantages over traditional (subtractive) manufacturing
  - Rapid prototyping
  - Fabrication of otherwise impossible objects
  - No need for high-volume manufacturing to be competitive
  - Cost for N products = N x cost of one product
  - Complexity and variety comes free
  - Less waste
- Spare parts production
- Manufacturing in space

http://www.nasa.gov/mission_pages/station/research/experiments/1115.html

Laser Diode in Material Processing

- Single laser diodes have optical power of the order of 10W and cannot be directly used for material processing, requiring several kW of optical power

- Beam Coupling of many laser diodes intrinsically reduces the total beam quality thus preventing use for material processing

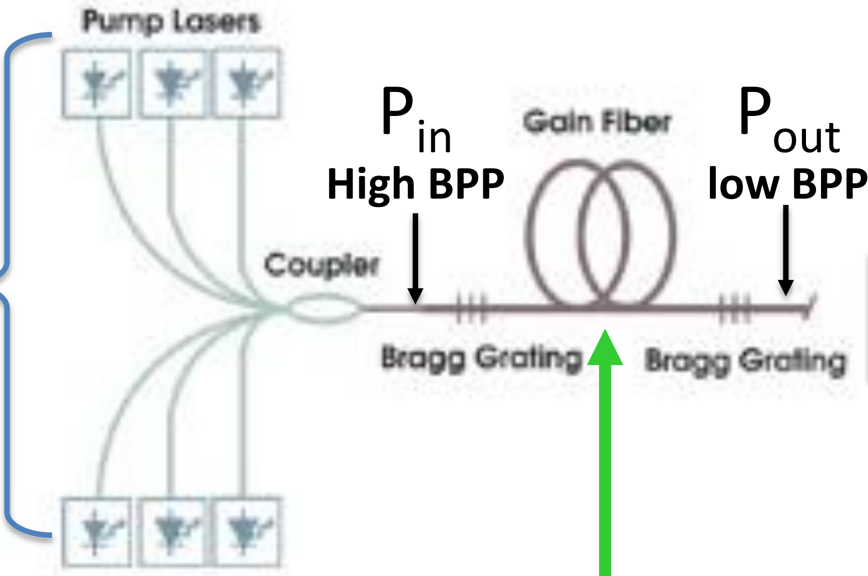
$$(BPP_{tot} \approx \sum BPP_i)$$

- Laser diode are typically used as pump sources for rare-earth-doped fiber lasers which in turn deliver the required kW optical power at low BPP

- The low BPP recovery is achieved at the expense of optical power loss of about 40%

Fiber Laser

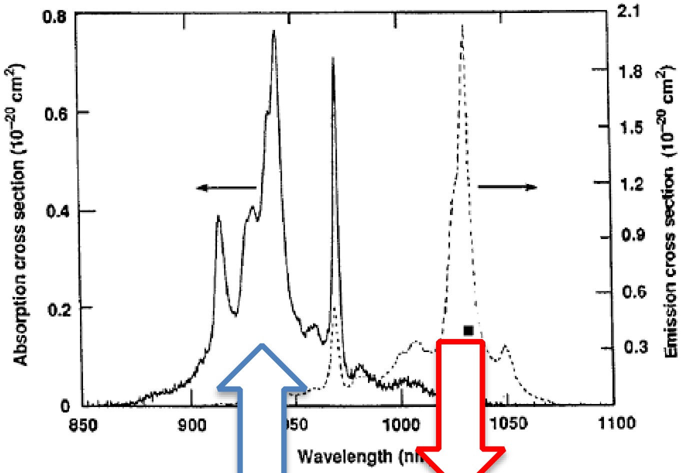
More than one hundred diodes for 1kW out **(high power at high BPP)**



P_{in}
High BPP

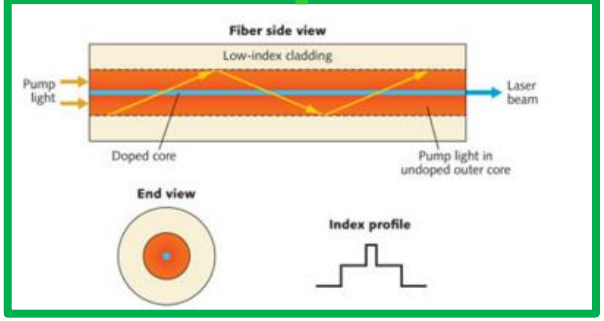
P_{out}
low BPP

kW power at low BPP



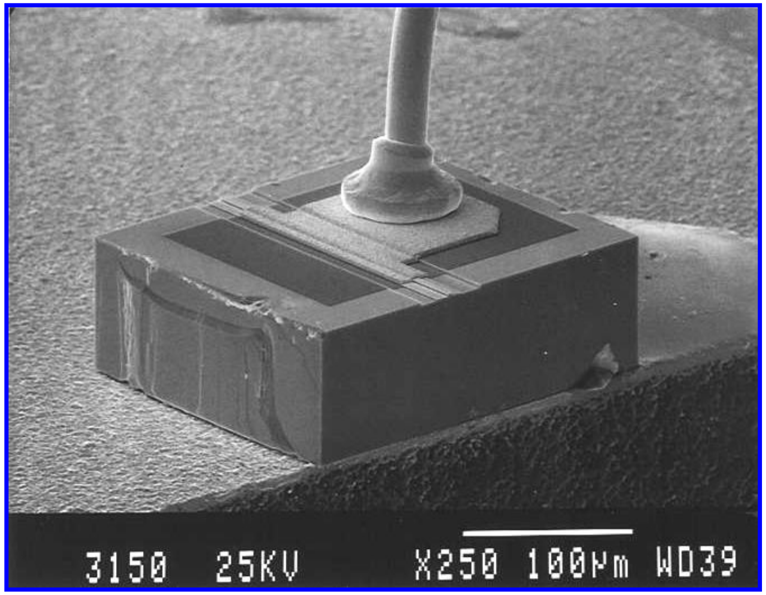
Optical Pumping

Fiber Laser Emission



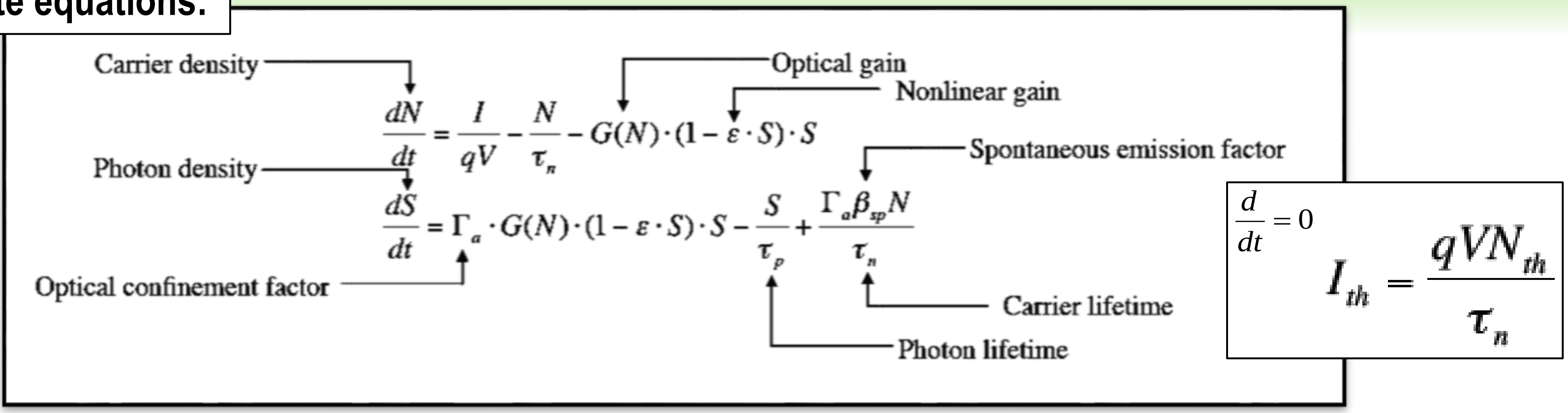
Active Fiber acts as a "BPP converter"

Semiconductor Laser
Principle of Operation and Key Points



Semiconductor 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 dens**ity in an **active material** within an **optical resonator**

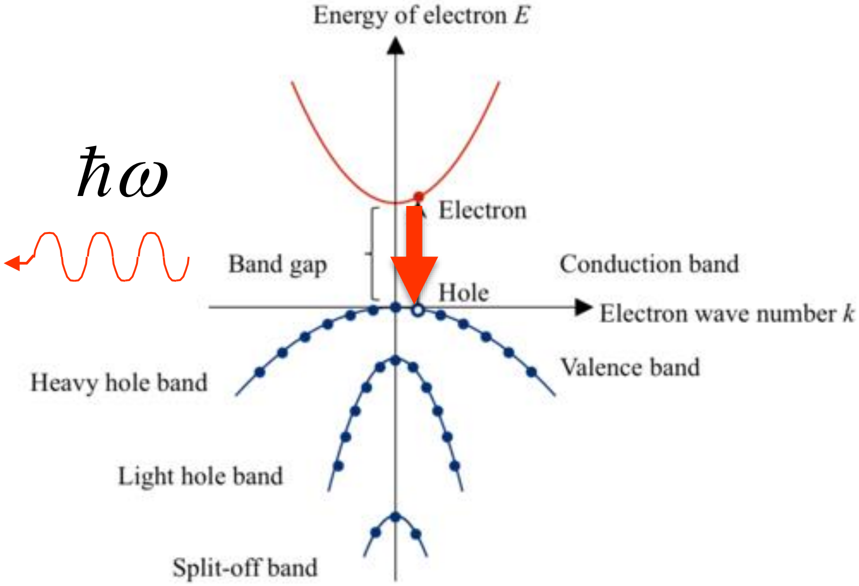
4

1. **Electrical injection** (p-n heterostructure)
   Carrier Confinement (Quantum Well)
2. **Photon confinement** (Optical Waveguide)
3. **Gain** (Quantum Well)
4. **Photon recirculation** (Facet Mirrors or Distributed Bragg Grating)

Semiconductor material basic requirements

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

photon emission
through e-h recombination



- ... at wavelength of interest:

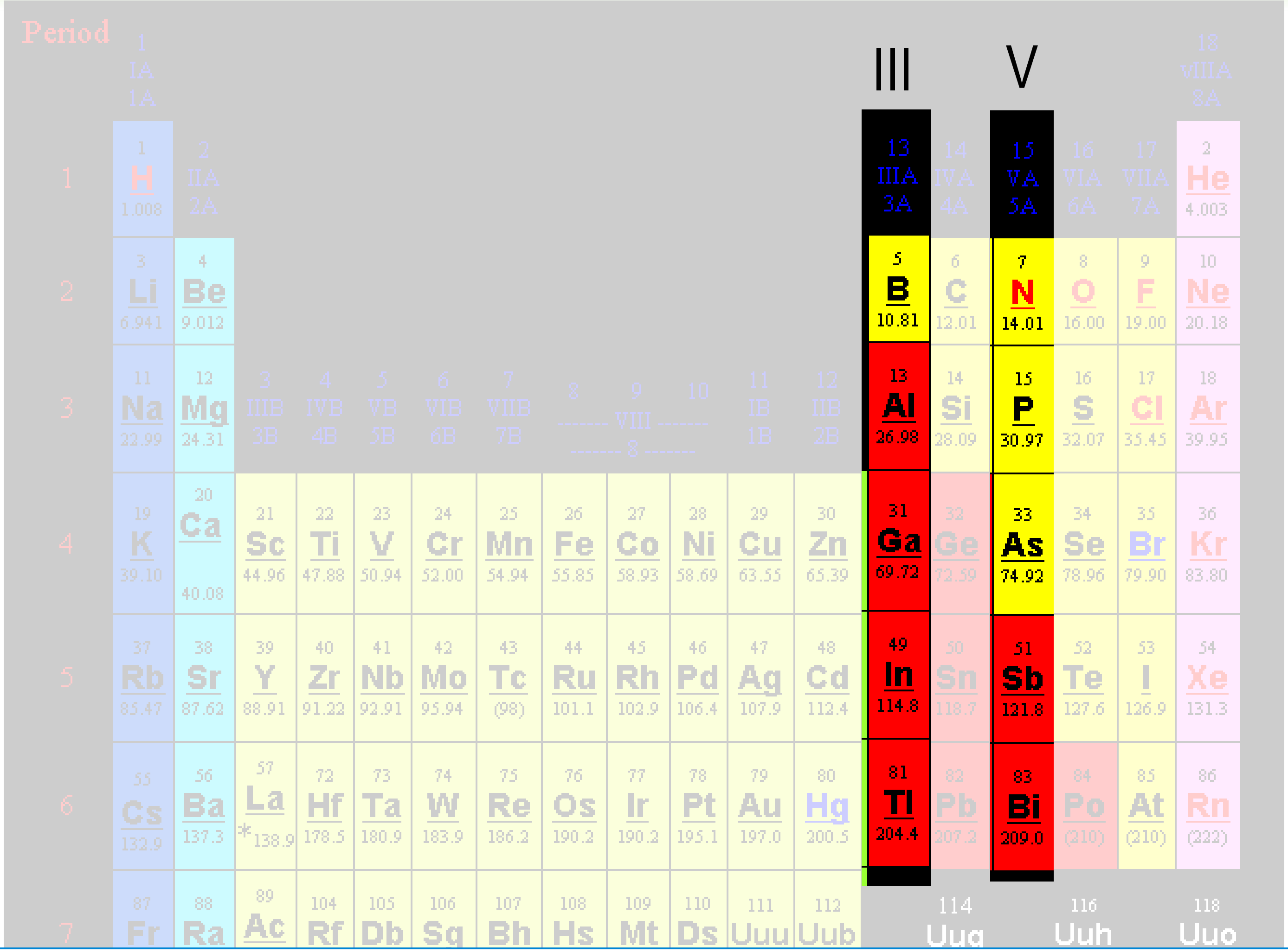
  Optical communication: λ = 1.3 μm, 1.55 μm

  Material processing (Yb pumping): λ = 0.90÷0.98 μm

  …

- compatibility with semiconductor substrates: Si, GaAs, InP

III-V semiconductor materials

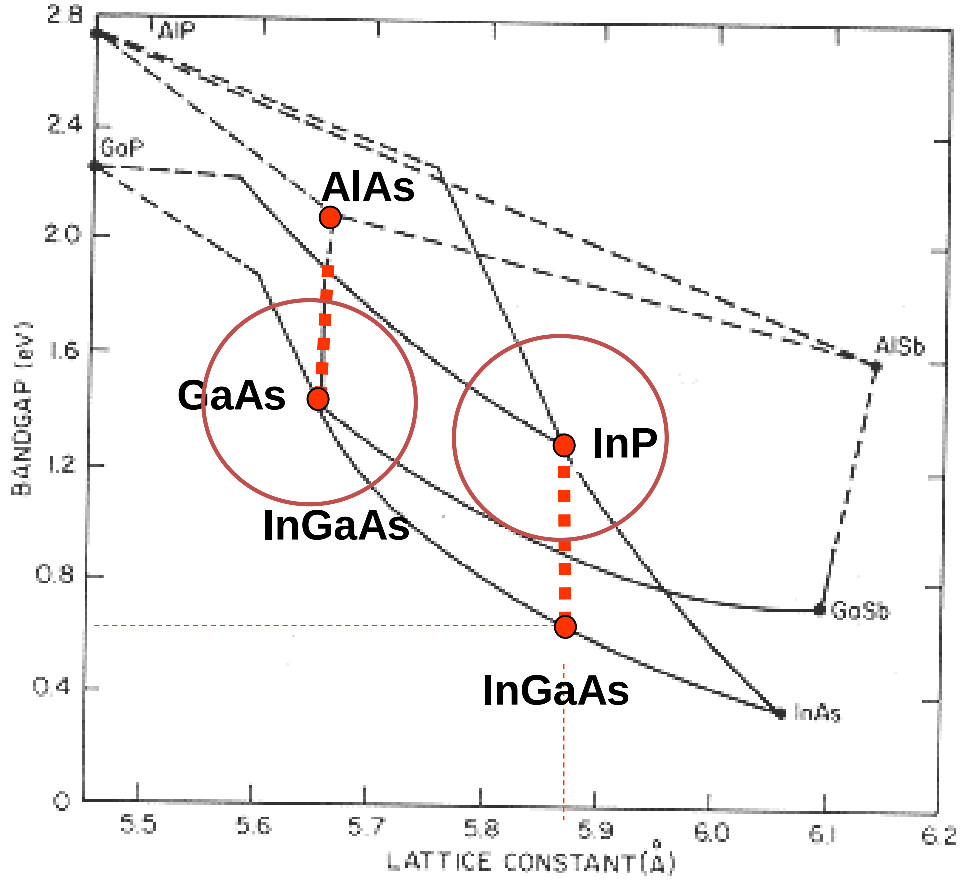


Period	1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9	10	11 IB 1B	12 IIB 2B	III 13 IIIA 3A	14 IVA 4A	V 15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57 La *138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 190.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.5	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Uuu	112 Uub		114 Uuq		116 Uuh		118 Uuo

Semiconductor alloys of III-V elements are the best materials for semiconductor lasers emitting at wavelength of interest

III-V alloys suited for the applications

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



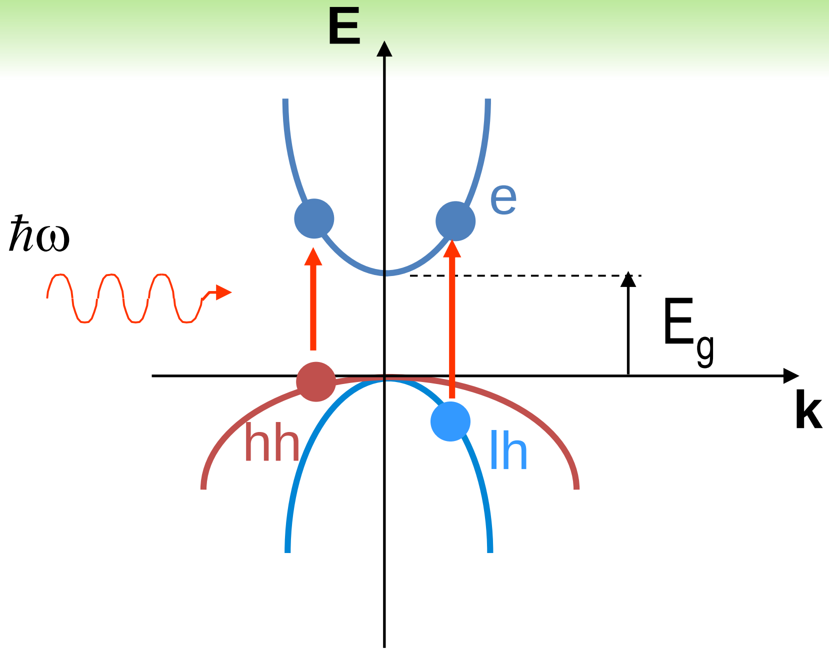
Variation of the bandgap as a function of lattice constant for III–V binary and alloy semiconductors

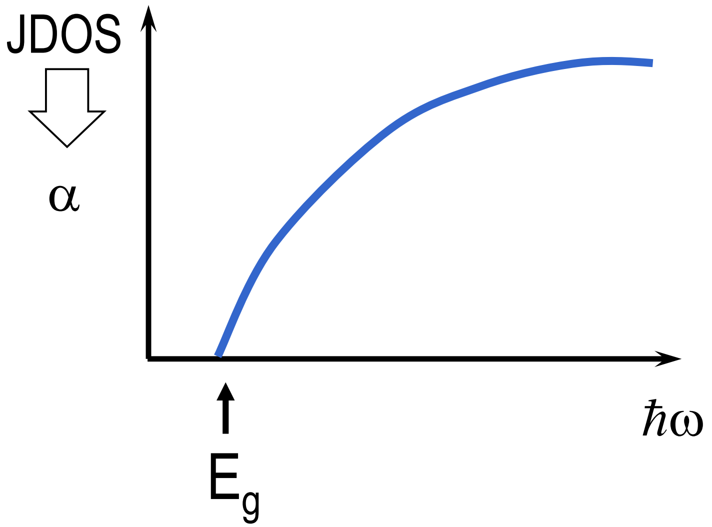
$In_{1-x}Ga_xAs_yP_{1-y}$ alloy, grown on InP substrate, covers the spectral range required for optical telecom

$Al_{1-x}Ga_xAs$ (+ $In_{1-x}Ga_xAs$) alloy, grown on GaAs substrate, covers the spectral range required for Yb-fiber laser pumping

- High quality material
- Established growth techniques and material processing

(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

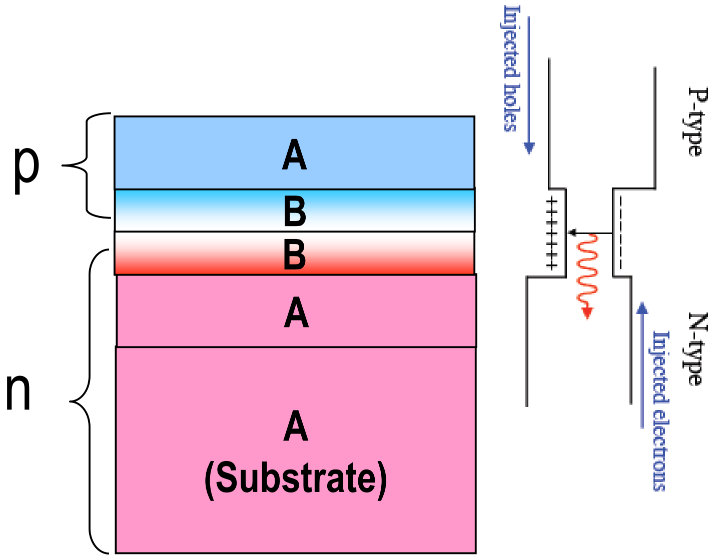
$$JDOS \propto \sqrt{\hbar\omega - E_g}$$

Semiconductor Heterostructures

Double Heterostructure (DH)

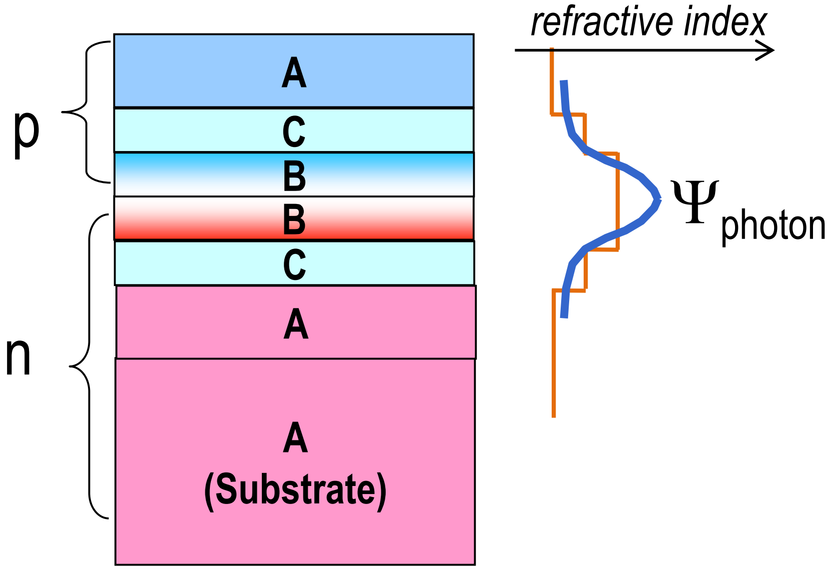
$\lambda_{ph} > \lambda_e$ ➡

Separate Confinement Heterostructure (SCH)



$E_g(A) > E_g(B)$

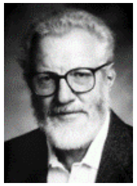
e-h confinement



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

Photon confinement

Combination of layers of different crystalline semiconductors.



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

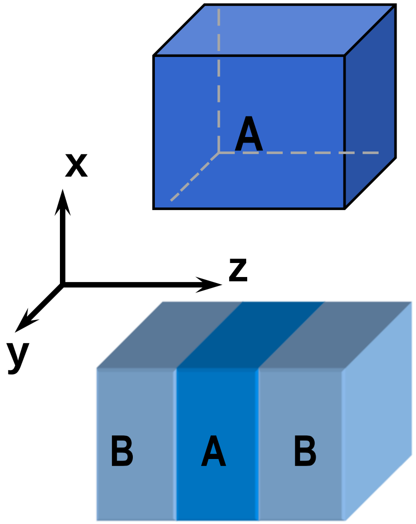
The idea was experimentally demonstrated using the Liquid Phase Epitaxy (LPE)

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).

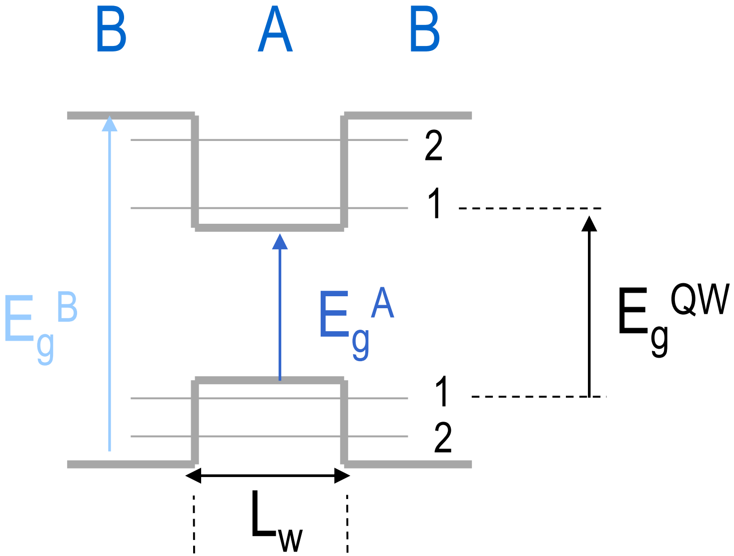


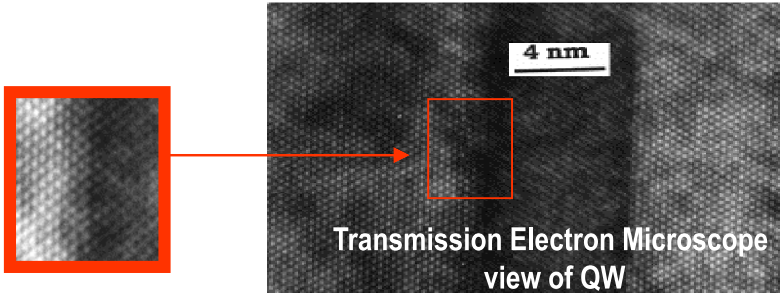
BULK

d = 3

QUANTUM WELL

d = 2 $L_w \sim \lambda_e$





Transmission Electron Microscope view of QW

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

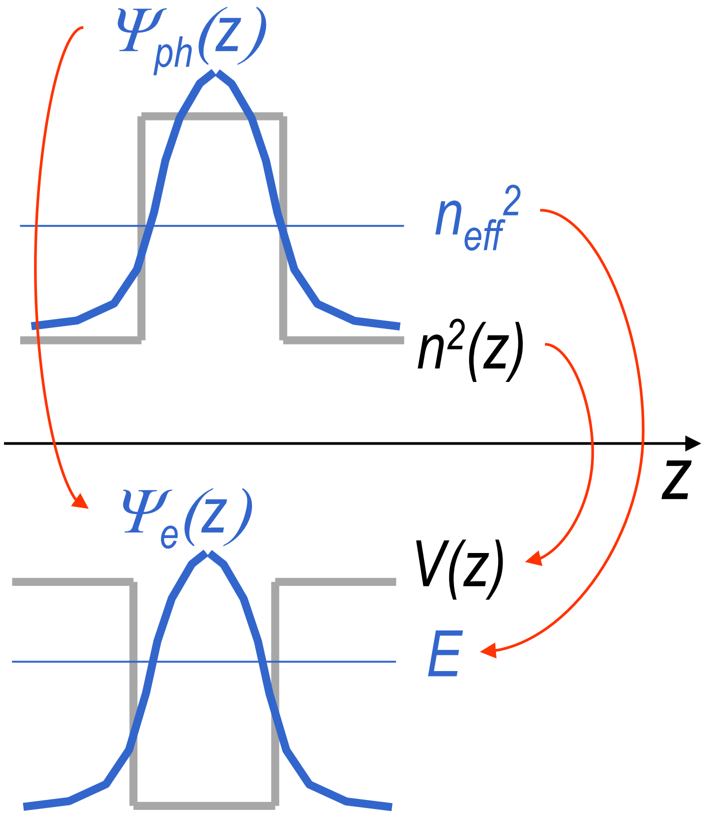
Photon wave eqn. vs. Electron wave eqn.

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*)

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



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

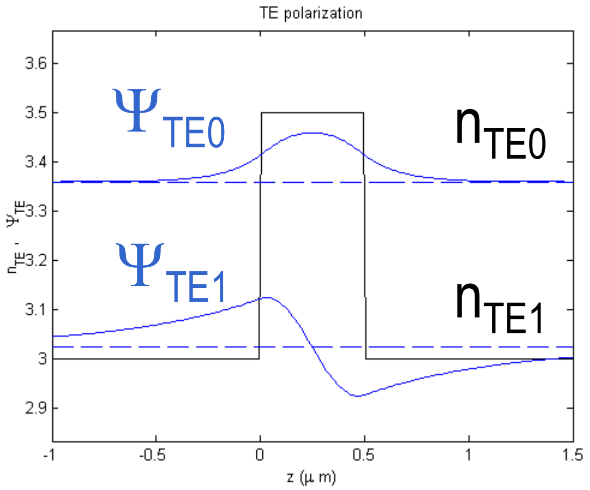
cladding $\Rightarrow$ barrier
core $\Rightarrow$ well

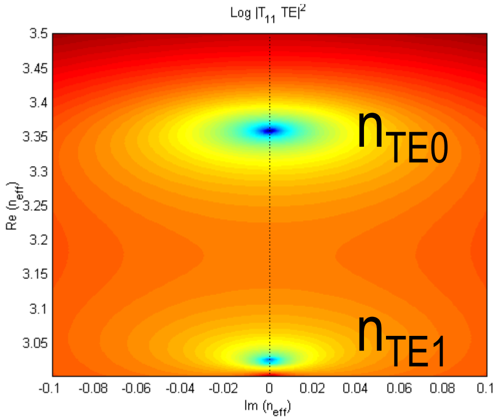
refractive index ridges confine photons (**optical waveguides**)

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

Eigenfunction/Eigenvalues Calculation

Optical Waveguide

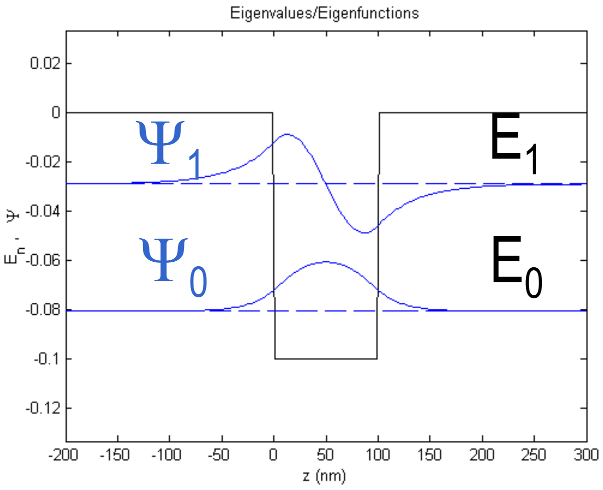


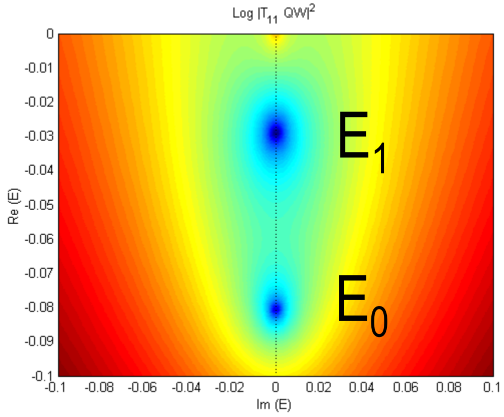


$$\Psi_{TE}(z^-) = \Psi_{TE}(z^+)$$

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

Quantum Well

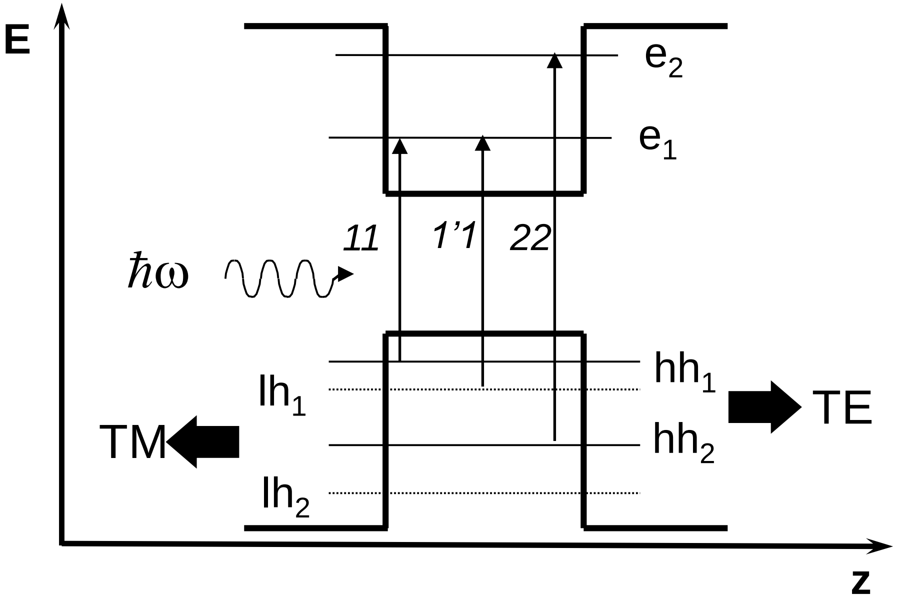




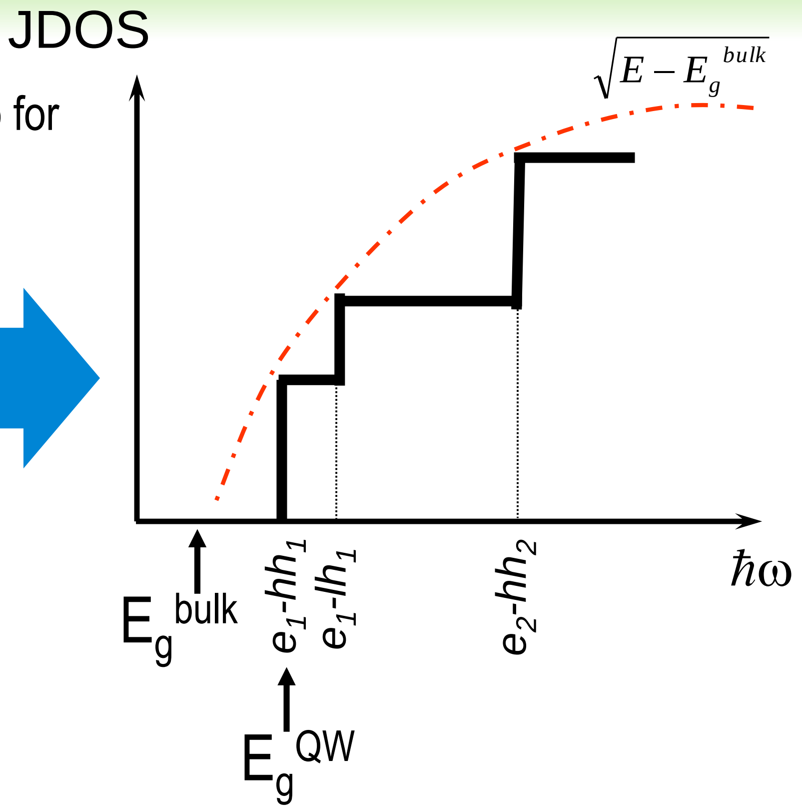
$$\Psi(z^-) = \Psi(z^+)$$

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

QW band structure



One step for every allowed transition



Strong carrier confinement and 2D Joint Density of States (JDOS):

- **Low laser threshold**
- **High thermal operation**
- **High differential gain**
- **Wide gain bandwith**
- . . .

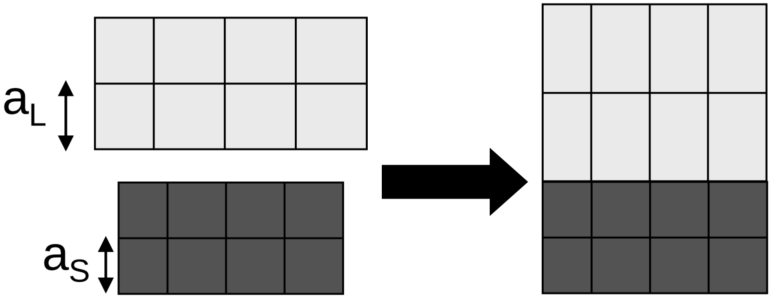
$$JDOS = \sum_{i\,j} \frac{\mu_{i\,j}}{\pi\,\hbar^2}\,\Theta\left(\hbar\omega - E_{i\,j}\right)$$

Strain(1)

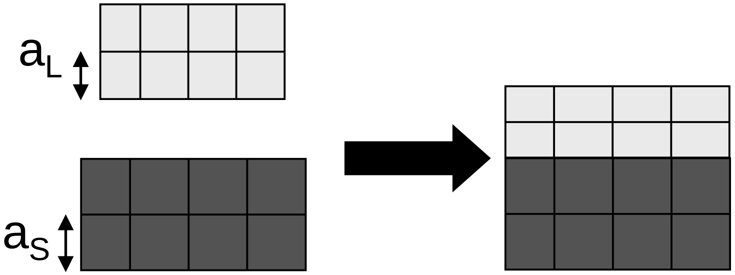
The epitaxial layer can be grown with a lattice parameter slightly different from the substrate lattice parameter (lattice mismatch).

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

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

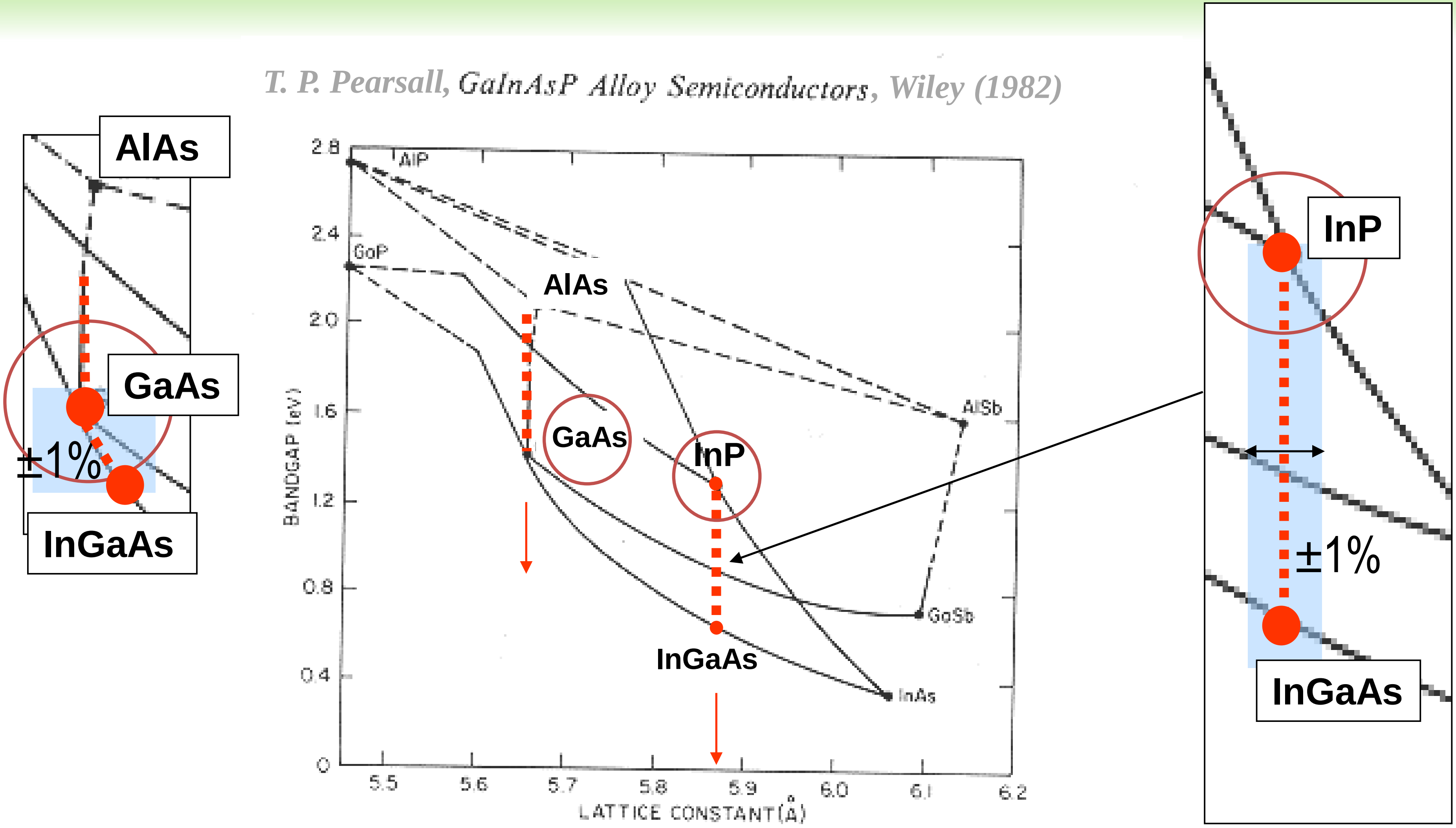


compressive strain
m>0



tensile strain
m<0

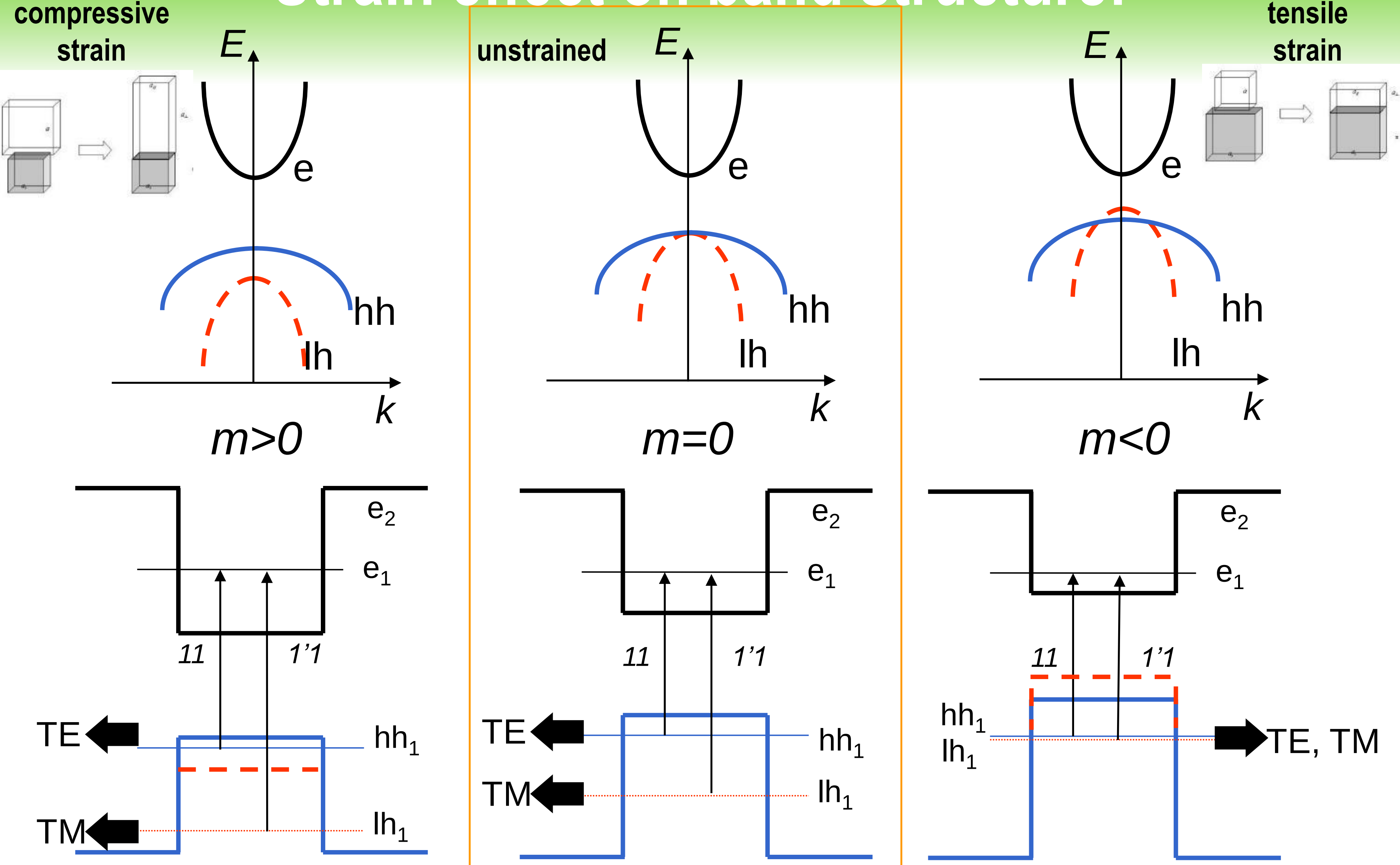
Strain(2)



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:

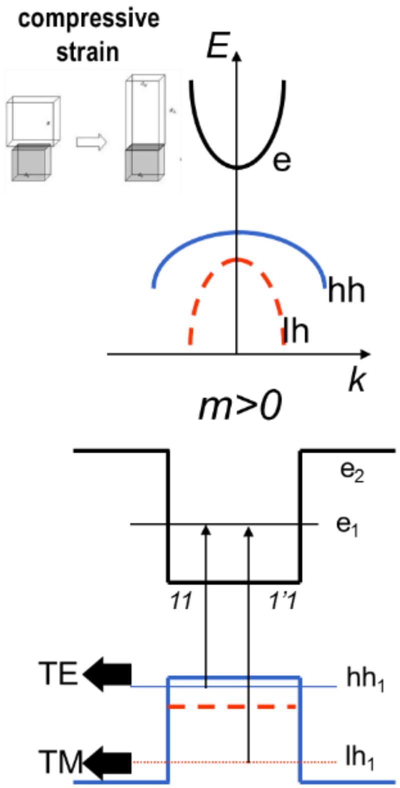


Low escape time
High T_0 (low thermal dependence)

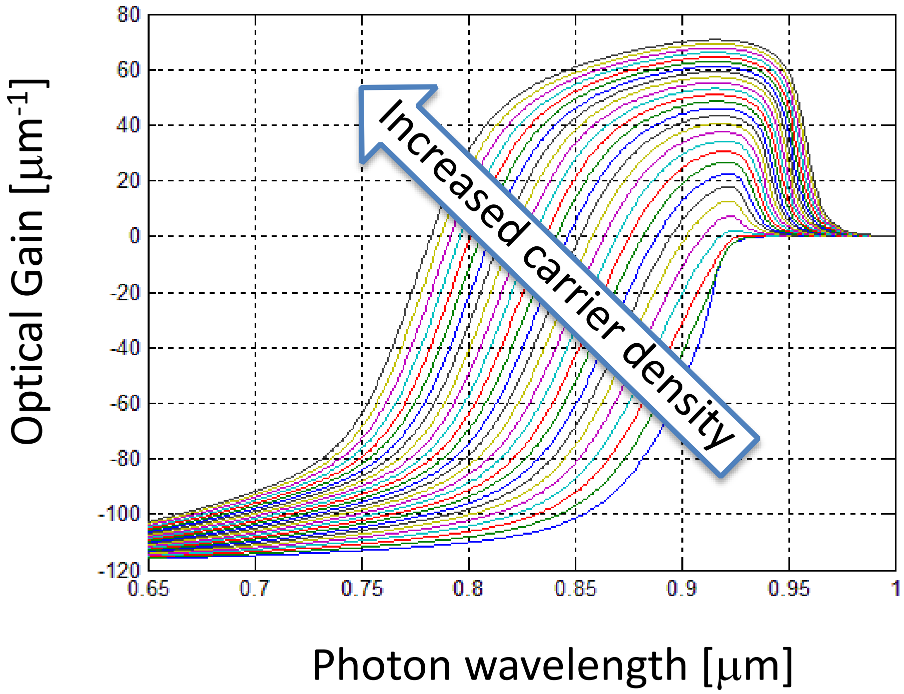
Low dichroism
Polarization-independent devices

Optical gain in Quantum Well

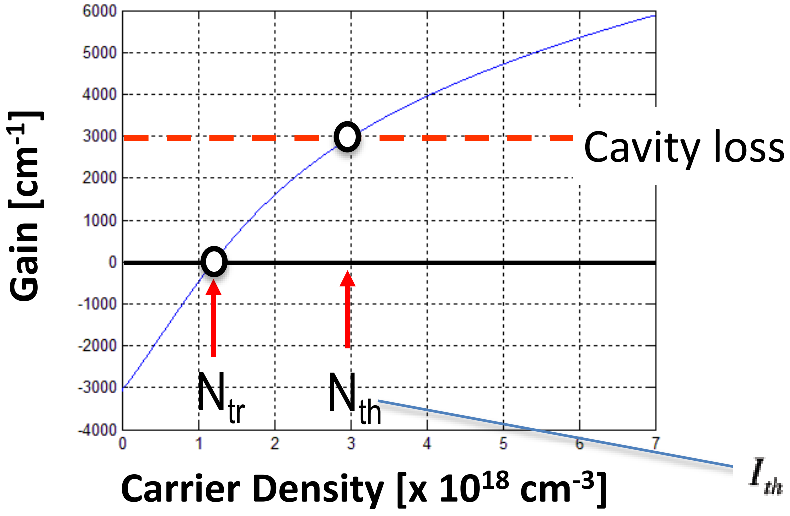
Tailored with quantum well structure (**thickness, composition, strain**)



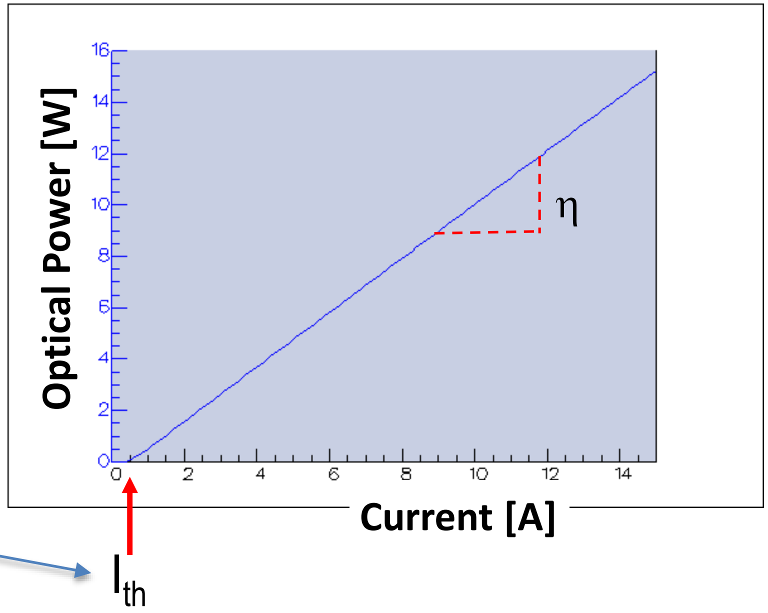
TE polarization



Optical properties of an high power laser



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



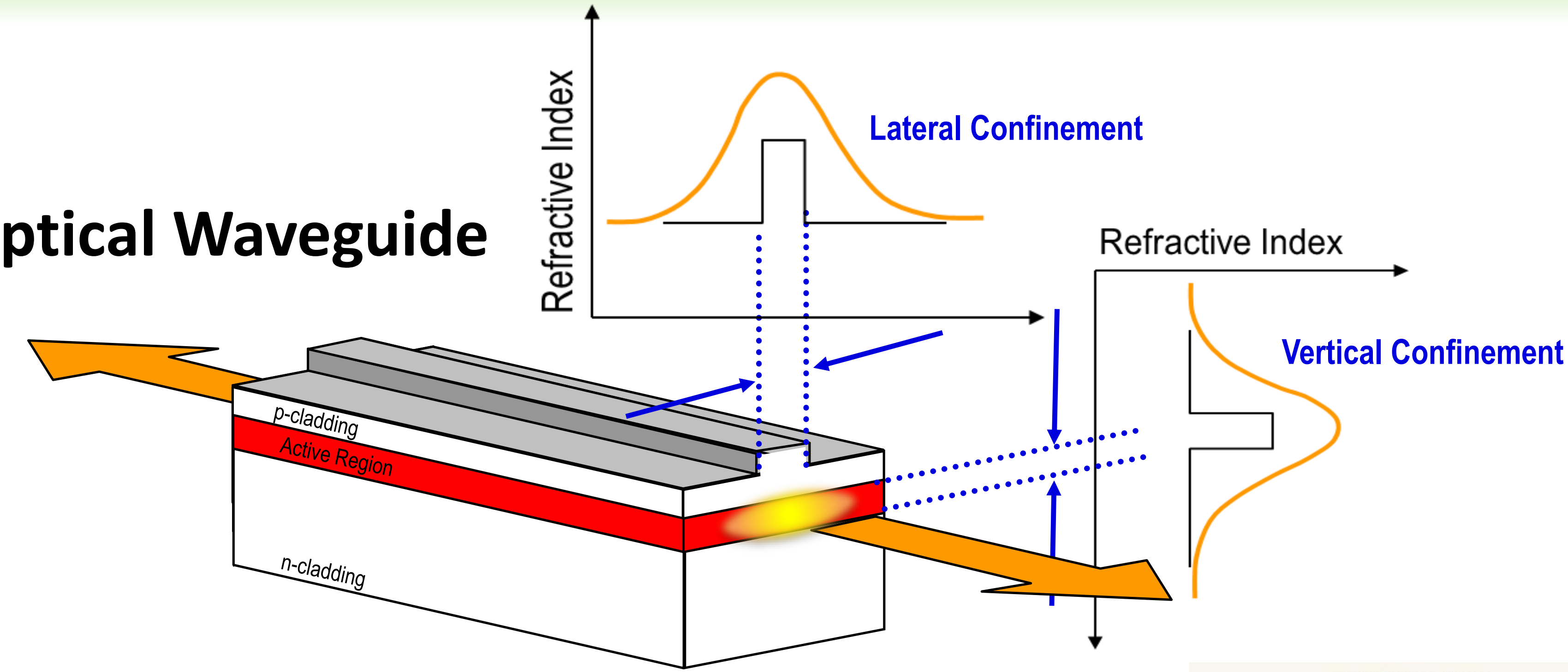
$$\eta = \frac{hc}{q\lambda}\eta_i \frac{\alpha_m}{\alpha_i+\alpha_m}$$ optical efficiency

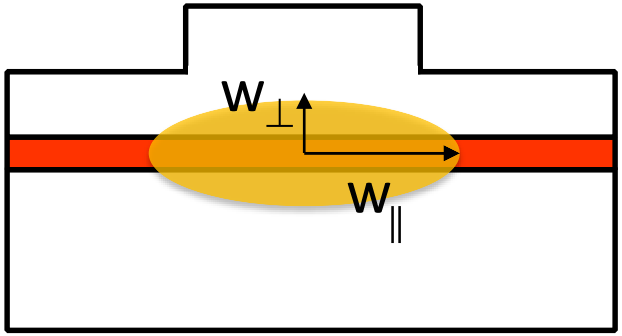
$$\alpha_m = \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)$$ mirror losses

Low dissipated power, high optical efficiency ⇒ long device length, low propagation loss

Optical Confinement

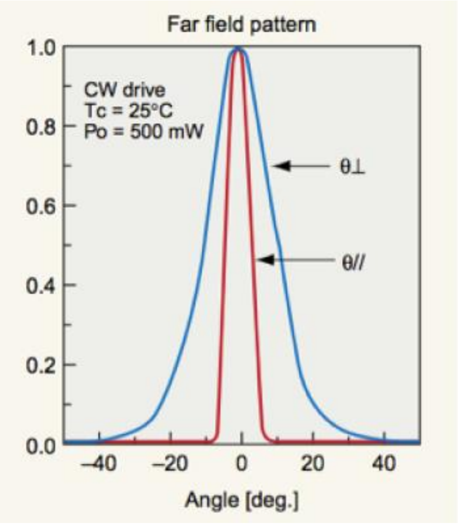
Optical Waveguide



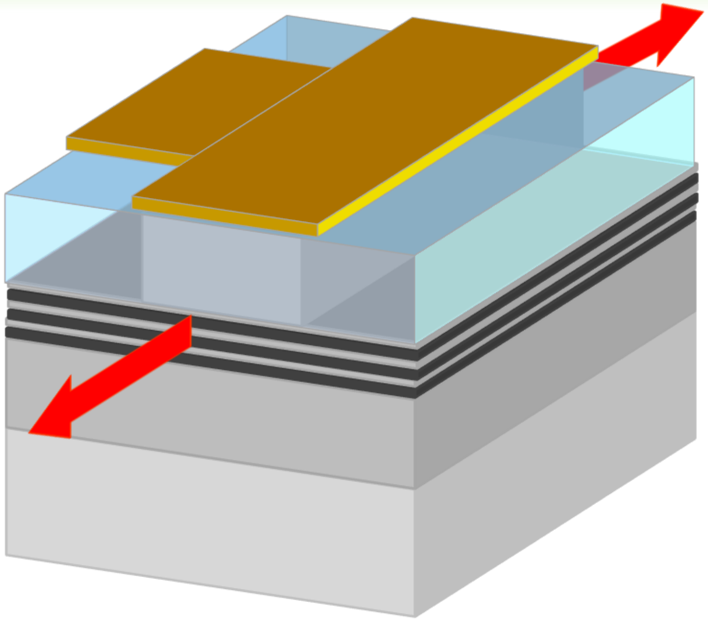


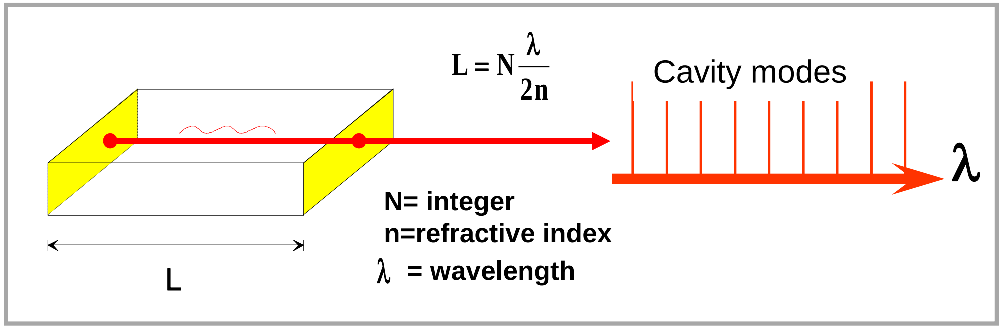
High-power laser:

- single mode in transverse direction (⊥), $w_\perp \approx 1\mu m$, $M_\perp^2 \approx 1$
- multimode in lateral direction, $w_{||} \approx 100\mu m$, $M_{||}^2 \approx 5$



Fabry Perot Laser (FP): Multi (longitudinal) mode

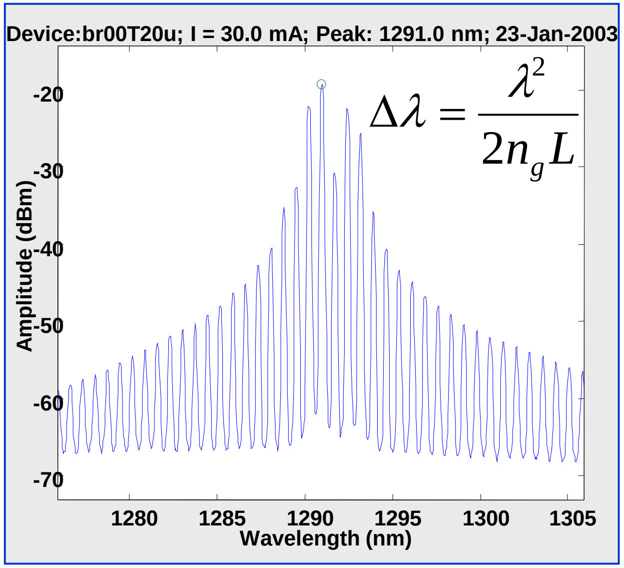




$$L = N\frac{\lambda}{2n}$$

N= integer
n=refractive index
λ = wavelength

Cavity mirrors are due to refractive index discontinuity from semiconductor active layer (n~3.2) and air



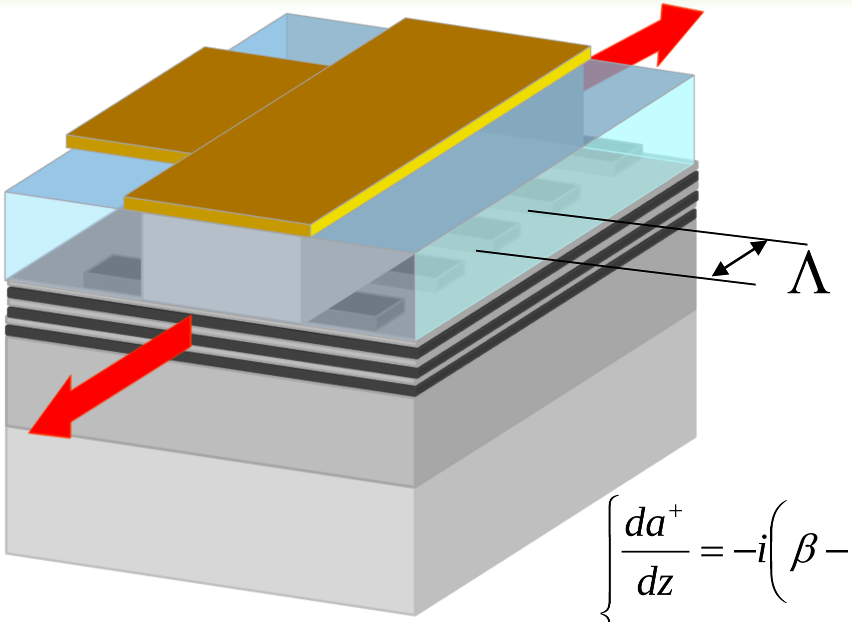
Device:br00T20u; I = 30.0 mA; Peak: 1291.0 nm; 23-Jan-2003

$$\Delta\lambda = \frac{\lambda^2}{2n_g L}$$

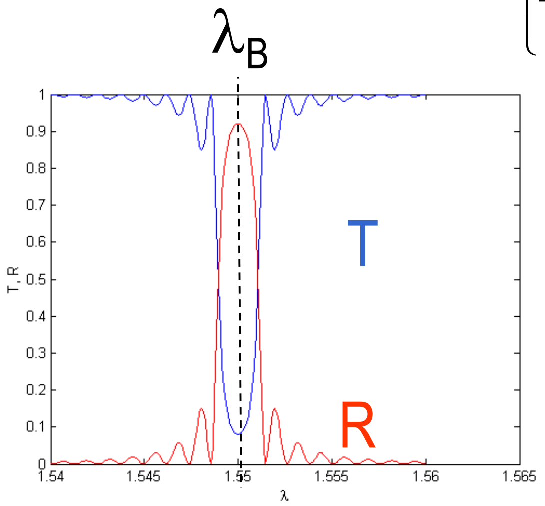
Multi-mode emission

Distributed Feedback Laser (DFB):

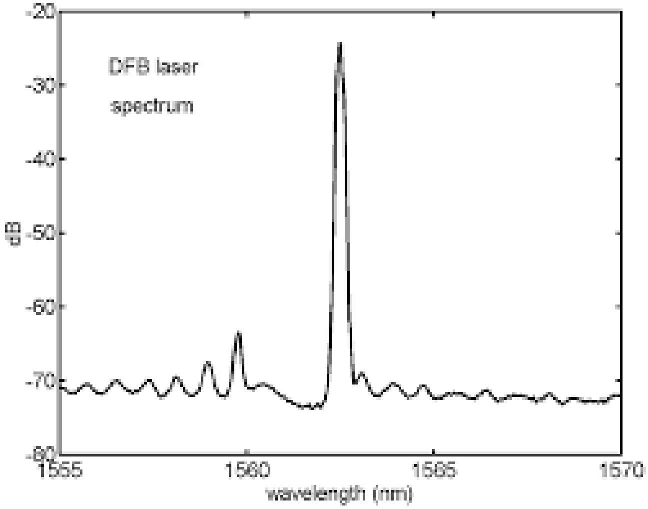
Single (longitudinal) mode



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

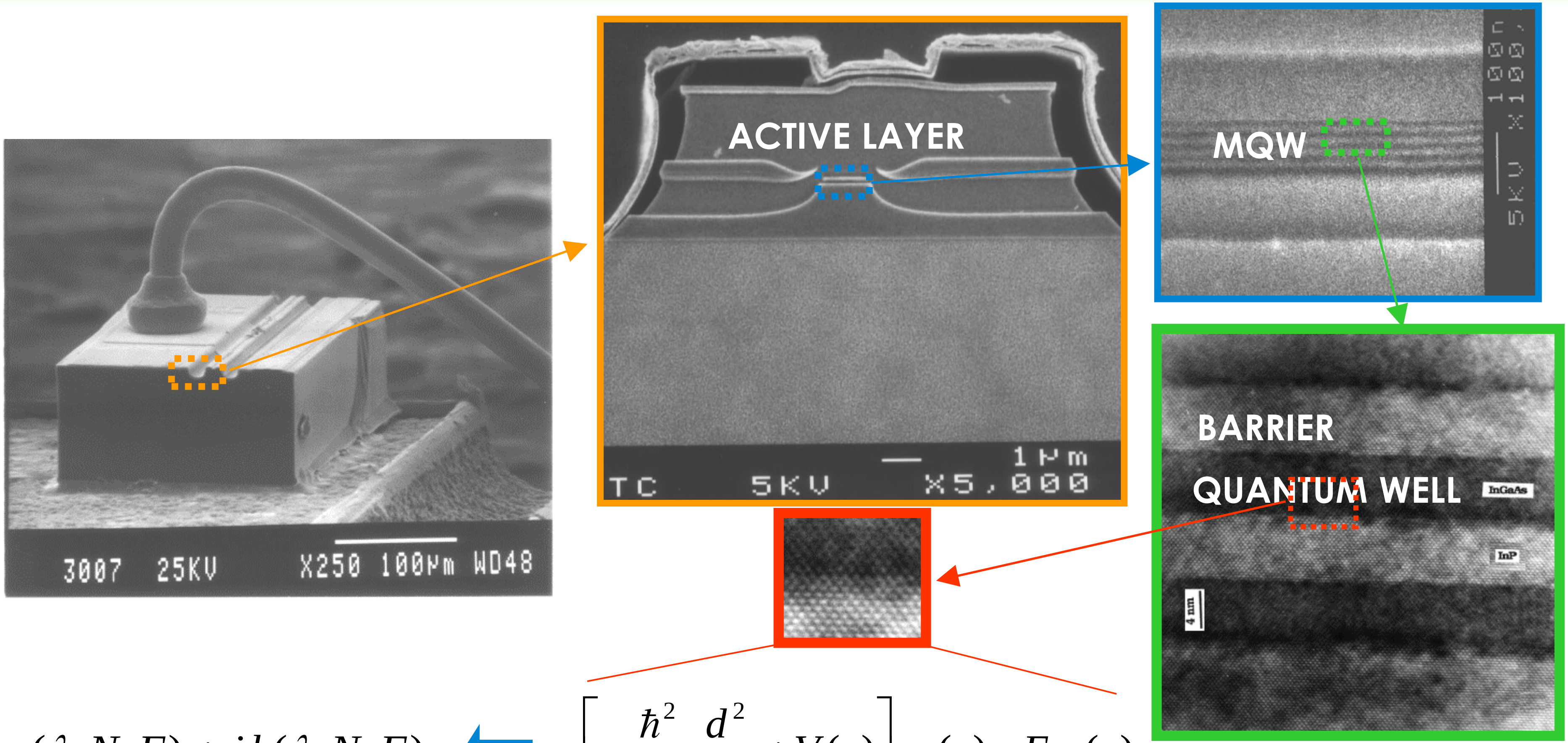


$$\begin{cases} \kappa = 65\ cm^{-1} \\ \Lambda = 0.24\mu m \\ \beta = \dfrac{2\pi}{\lambda}\cdot 3.2 \end{cases}$$



Quantum Wells:

Atomic-Controlled Artificial Structures



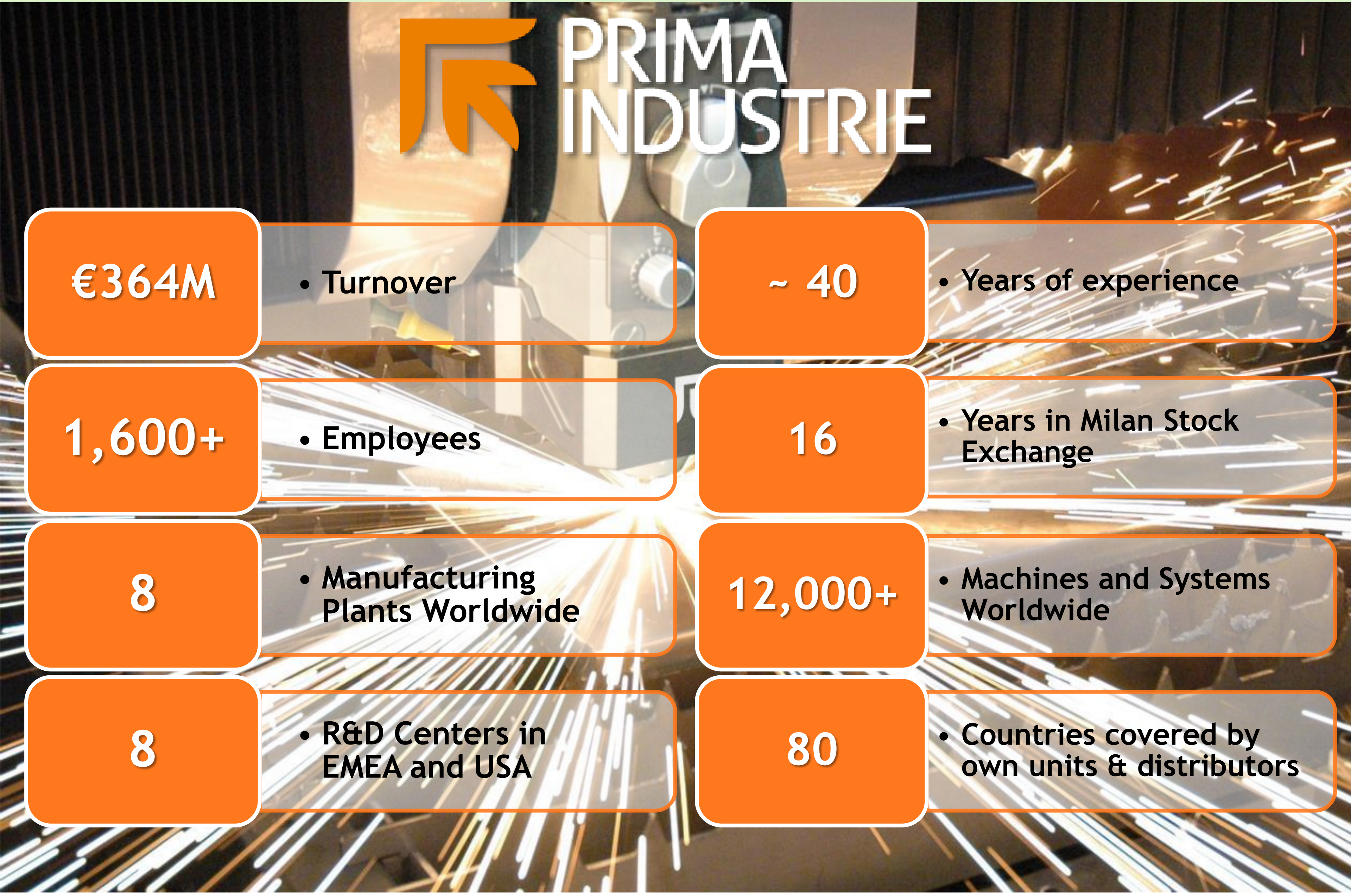
$$n(\lambda,N,F)+i\,k(\lambda,N,F) \Leftarrow \left[-\frac{\hbar^2}{2m}\frac{d^2}{dz^2}+V(z)\right]\psi(z)=E\psi(z)$$

Control of Optical Properties through atomic-scale technology
Quantum Well requires sub-monolayer manufacturing control ($\sigma < 0.1$nm over 10cm^2)
achievable with Molecular Beam Epitaxy or Metal Organic Chemical Vapor Deposition.

Prima
Electro

Company Snapshot

PRIMA INDUSTRIE: 2015 Facts & Figures



PRIMA INDUSTRIE

€364M	• Turnover
1,600+	• Employees
8	• Manufacturing Plants Worldwide
8	• R&D Centers in EMEA and USA
~ 40	• Years of experience
16	• Years in Milan Stock Exchange
12,000+	• Machines and Systems Worldwide
80	• Countries covered by own units & distributors

PI Group Divisions

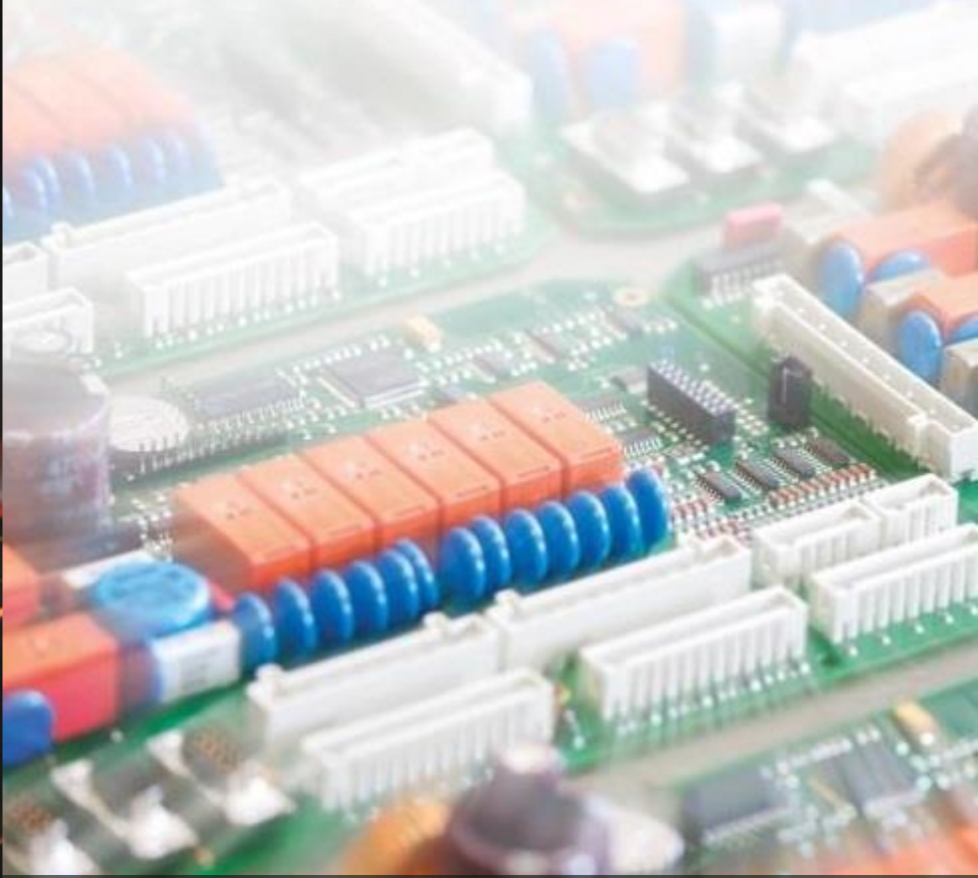
Prima Power

Machinery Division

Laser and sheet metal fabrication machinery: 3D laser cutting, welding/drilling, punching, combined tech, bending, automation and FMS.

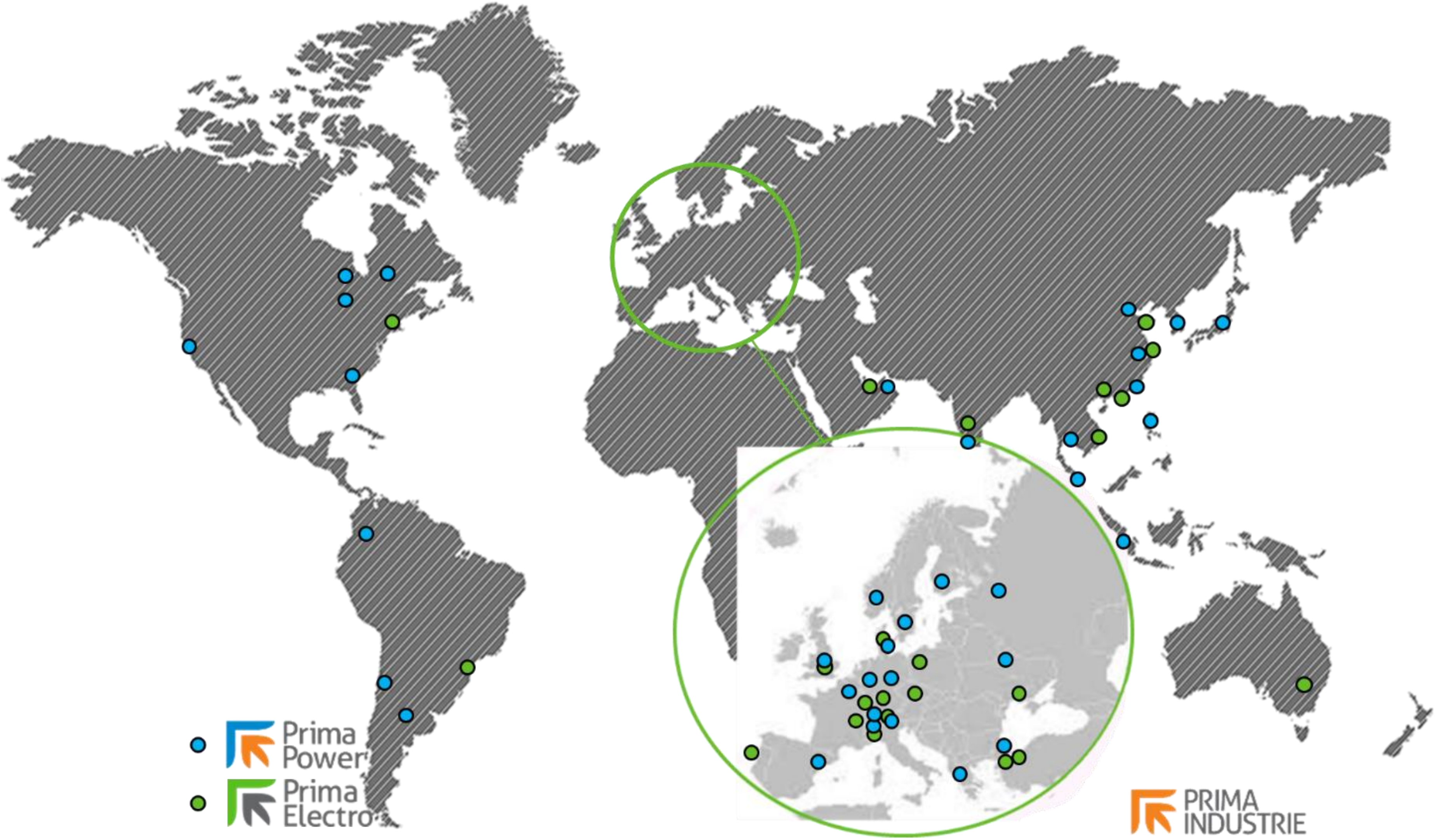
Prima Electro

Electronic Division



Industrial grade dedicated electronics, numerical controls & motions systems and high power laser sources for industrial applications.

PI worldwide



R&D and Manufacturing Plants

Champlin (MN) - USA

Laserdyne and 3D laser systems

Collegno (TO) - Italy

2D and 3D Laser systems

Kauhava - Finland

Punching & Combi systems - Automation

Cologna (VR) - Italy

Panel benders & press-brakes

Chicopee (MA) - USA

Convergent Photonics laser sources

Barone (TO) - Italy

Electronics: OSAI and DOTS products assembly & testing

Moncalieri (TO) - Italy

Electronics: R&D lab and board processing

Torino - Italy

R&D - Semiconductors Lab

Suzhou - China

2D laser systems & punching for Chinese & Asian market

🟦 Prima Power

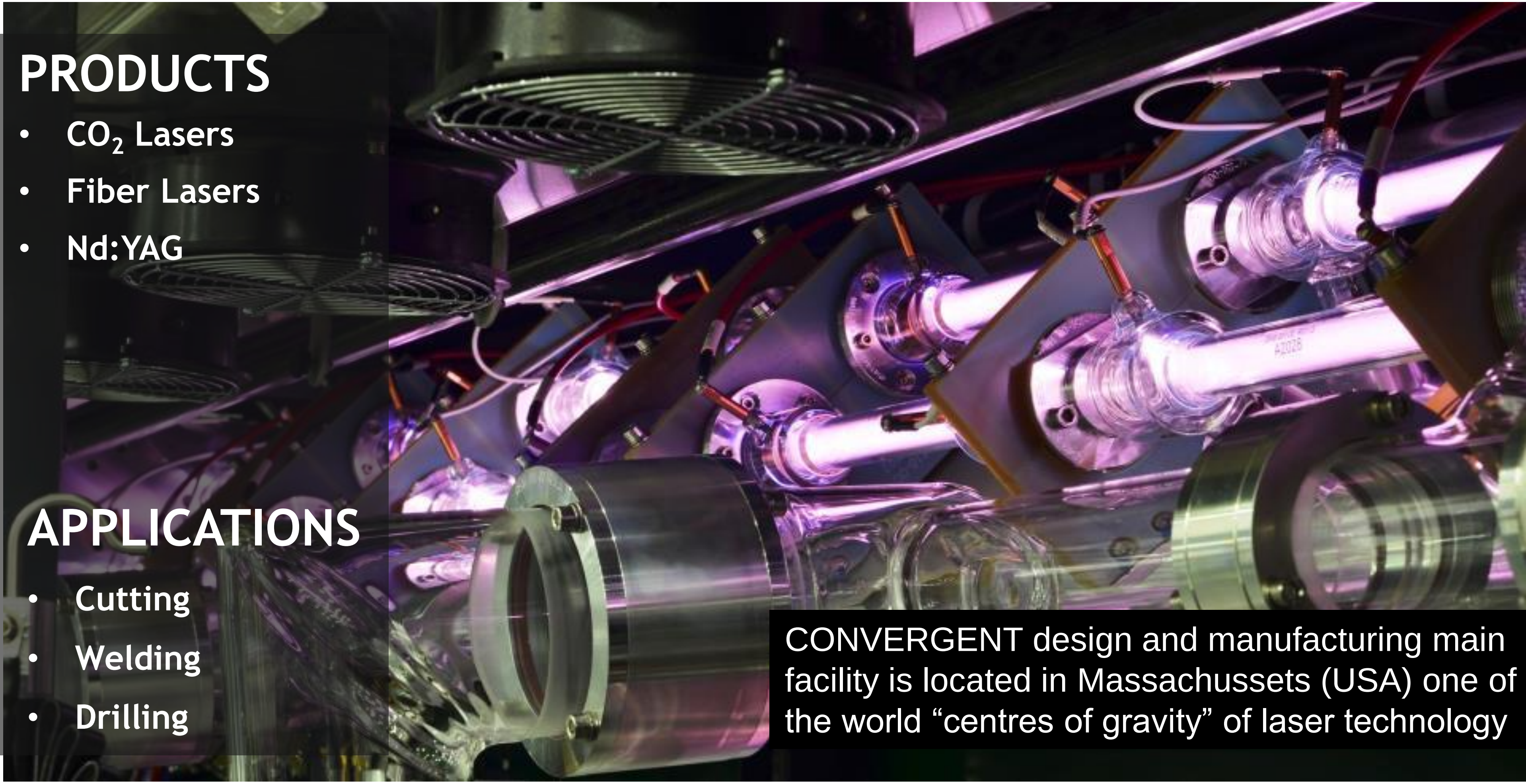
🟩 Prima Electro

PRIMA INDUSTRIE

convergent

Laser Sources

Cutting, welding, and drilling applications of **metallic** and **non-metallic** materials. Over 6000 high power industrial laser sources worldwide.



PRODUCTS

- CO_2 Lasers
- Fiber Lasers
- Nd:YAG

APPLICATIONS

- Cutting
- Welding
- Drilling

CONVERGENT design and manufacturing main facility is located in Massachussets (USA) one of the world “centres of gravity” of laser technology

Torino Diode Fab

Diode Fab Team R&D and Production background

Team History

1980 1990 2000 2010

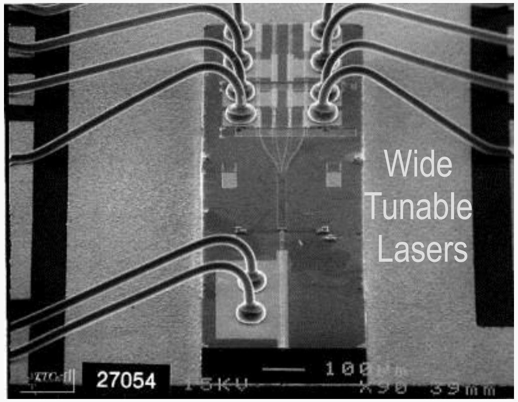
CSELT

Agilent - Avago

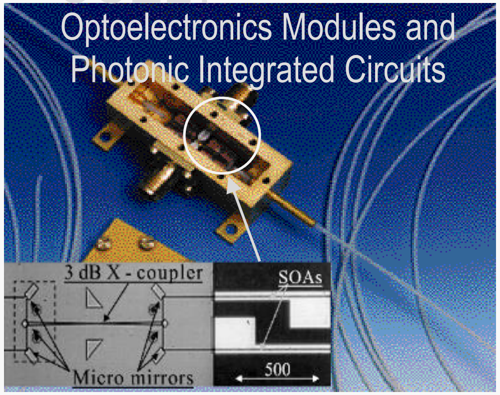
Telecom Italia Research Center "CSELT"

Team heritage is a long path of Research, Development and Production of Photonic devices for telecom

- As Optical Technology Research Center for Telecom Italia (CSELT – Tilab) since 1980; from 2000 to 2014 as R&D and Production center for Agilent / Avago technologies
- Developing know how on modeling, EPI growth and Technology Processes on semiconductor for Photonic devices
- 2007 - 2014, developing key competences on production engineering for telecom laser sources



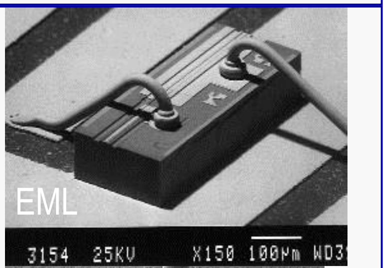
Wide Tunable Lasers



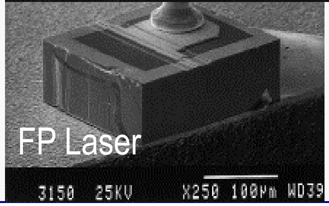
Optoelectronics Modules and Photonic Integrated Circuits

Production lasers in Torino (2007 - 2014)

- **2 Million diodes shipped to product line**
- **Proven reliability:**
  - **No return from field**
  - **70 M device x hours tested in Lab**



EML

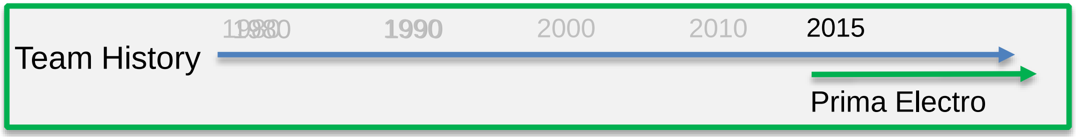


FP Laser

Prima Electro

Diode Fab Today

Prima Electro



From January 2015, a new R&D centre has been opened in Torino as part of Prima Electro and in co-operation with:

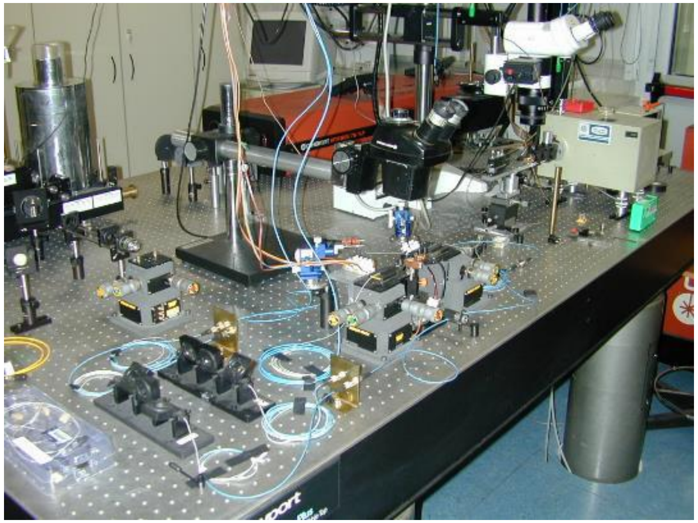
POLITECNICO DI TORINO

OPI Photonics

Mission: to develop Semiconductor and High Power Laser Technologies for industrial applications

Team skills:

12 engineers, core competency of R&D and production of diode lasers



- ElectroMagnetic, Quantum Mechanical, Electrical and Thermal Design
- Technology Know How (Wafer Fab, Die Fab)
- Production Engineering
- Testing and Characterization
- Stress test of optoelectronic devices (new product qualification, production quality)

Semiconductor Lab

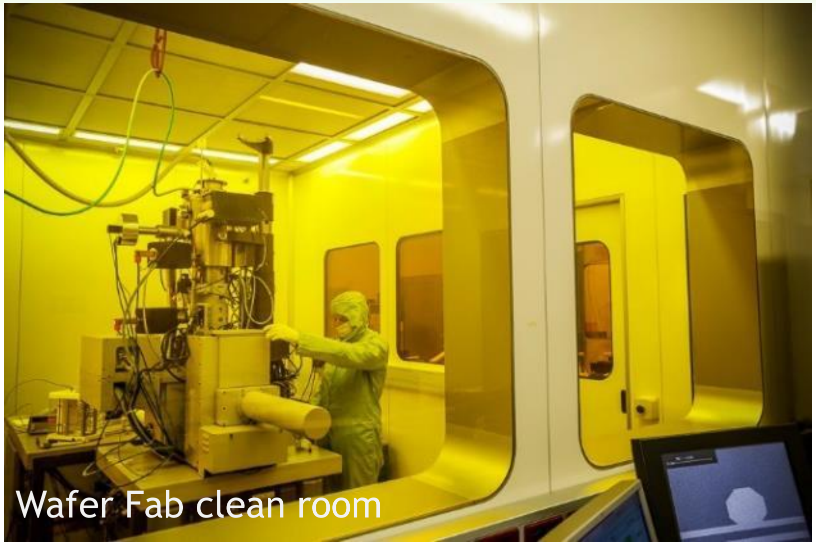
Facilities

Site Numbers:

- ☐ Clean Rooms (10 -10000 class):
  - 800 m2 Wafer Fab:
  - 400 m2 Die Fab, Testing:
- ☐ Stress Test (reliability): 100 m2
- ☐ 600 m2 of R&D Lab for Diode Laser testing, offices, meeting Room

Facilities:

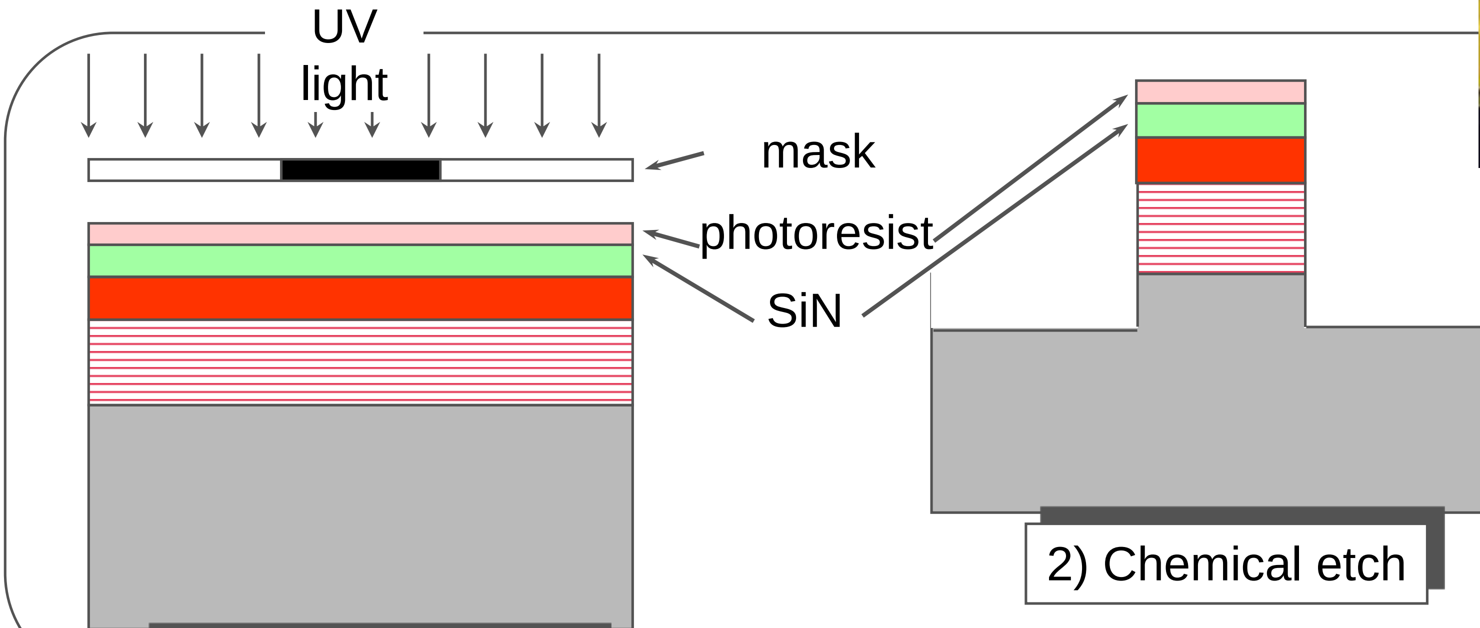
- ☐ Dielectric and metal deposition, wet and dry etching, nano-scale Lithography (EBL)
- ☐ Automatic testing, Wafer Scribing, Chip-on-Carrier assembly
- ☐ Stress tests and wafer validation (Burn In , Lifetest)
- ☐ Multiemitter modules assembly line (2016)



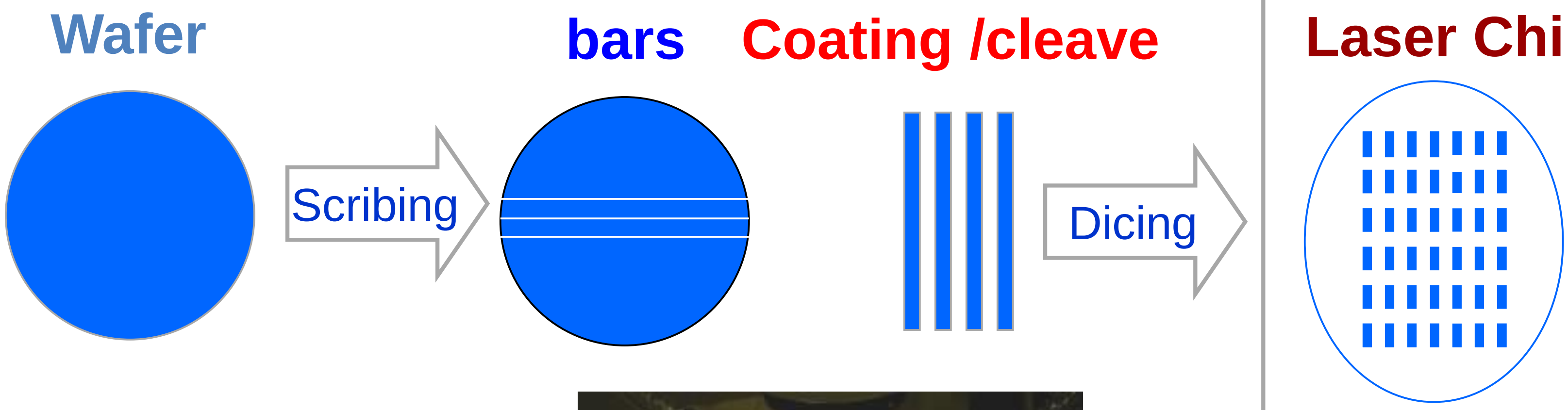
Wafer Fab clean room

Die Fab clean room

How to make laser diodes: Wafer process



How to make laser diodes: Die Process: from wafers to chips



Wafer

Scribing

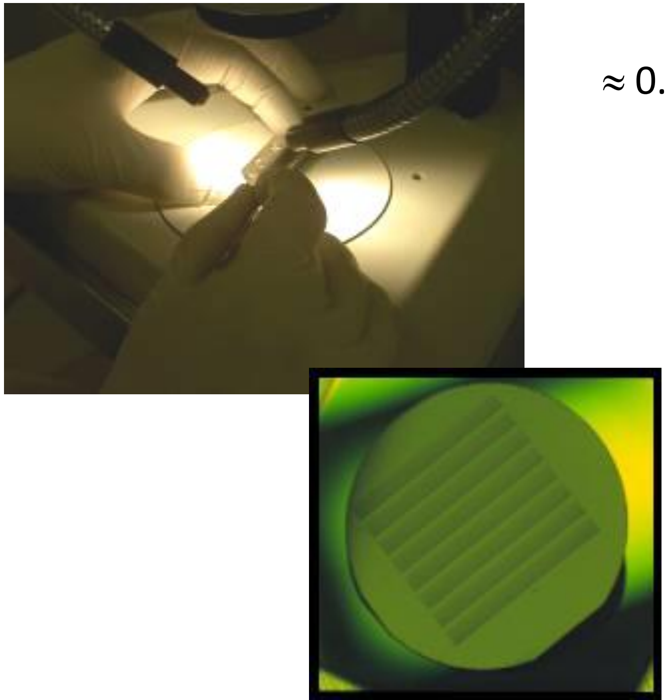
bars

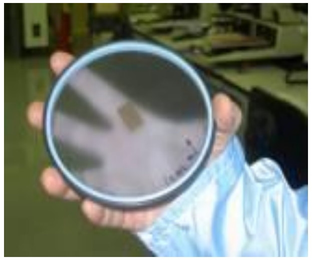
Coating /cleave

Dicing

Laser Chips

≈ 0.6mm(w) x 5mm(L) x 0.1mm(h)





Thanks for your attention!

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