MSc in Photonics & Europhotonics

Laser Systems and Applications 2018-2019

Semiconductor light sources

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Outline

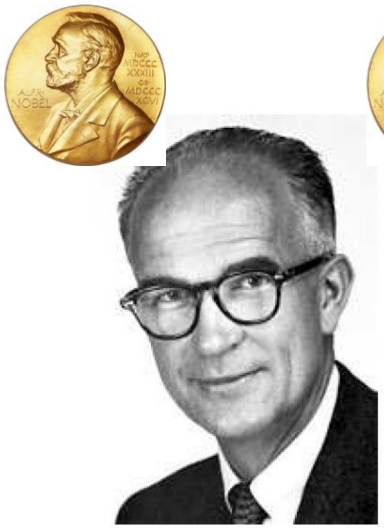
- Introduction
- Semiconductor materials
- Photons in semiconductors
- Semiconductor light sources
  - LEDs
  - Amplifiers
  - Semiconductor lasers

Learning objectives

Acquire a basic knowledge of

- Semiconductor materials and wavelengths
- Operation principles of semiconductor light sources
- Design and fabrication
- Static and dynamics characteristics
- New materials and cavity types

The Nobel Prize in Physics 1956



William Bradford Shockley

John Bardeen

Walter Houser Brattain

"*For their research on semiconductors and their discovery of the* ***transistor*** *effect*".

The invention of the transistor at Bell labs in **1947** lead to the development of the semiconductor industry (microchips, computers and LEDs –initially only **green**, **yellow** and **red**)

The Nobel Prize in Physics 2018

Arthur Ashkin (Bell Laboratories, USA): laser-based ***optical tweezers*** that capture, move and measure forces on small objects.

Gérard Mourou (École Polytechnique, France) and Donna Strickland (University of Waterloo, Canada): ***chirped-pulse amplification*** (CPA), the technique that has allowed vast advances in the power of ultrafast pulsed lasers.

The first working laser

- Attributed to Theodore Maiman (at Hughes Research Laboratories) that in **1960** demonstrated the first working laser: MASER, for "Microwave Amplification by Stimulated Emission of Radiation“.
- His paper was published in Nature (rejected from PRL).
- In 1962, Maiman founded Korad Corporation to develop and manufacture a line of high-powered laser equipment. Korad became the market leader in its field.
- Meantime, in **1957** Arthur Schawlow and Charles Townes constructed an optical cavity by placing two highly reflecting mirrors parallel to each other, and positioning the amplifying medium in between.
- In **1958** they published (Physical Review) their findings and submitted a patent application for the so-called optical maser.

Source: laserfest.org

First laser patent

- Awarded in **1960** to Arthur Schawlow and Charles Townes.
- "Thirty Year Patent War“ with Gordon Gould, a graduate student at Columbia University that was the first to publically use the term laser, for "Light Amplification by Stimulated Emission of Radiation"
- Since then, more than 55,000 patents involving the laser have been granted in the United States.

Source: laserfest.org

2012: 50th anniversary of the semiconductor laser

- First demonstration: **1962** (pulsed operation, cryogenic temperatures).
- Four research groups in the USA almost simultaneously reported a functioning semiconductor laser based on gallium arsenide crystals (GaAs).
- Three of the papers were published in the same volume of APL; the other one in PRL
  - Marshall Nathan of IBM,
  - Robert Rediker of MIT,
  - Robert Hall and Nick Holonyak from two different General Electric Company labs.

Robert Hall

Source: Nature Photonics December 2012

On the discovery of the diode laser

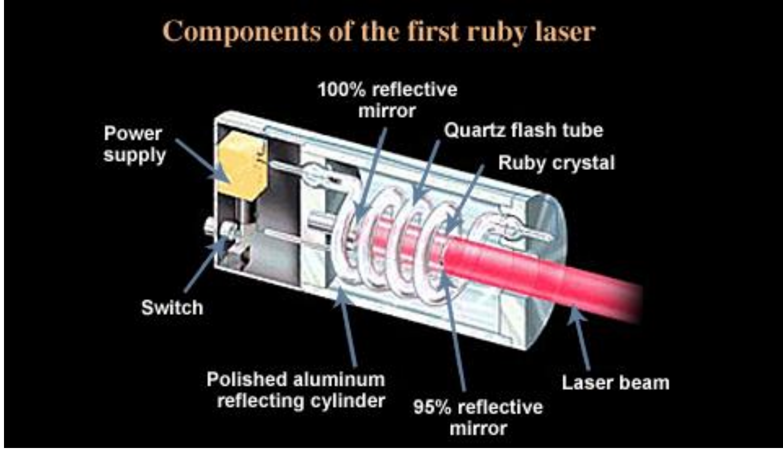
- Early 1962 Marshall Nathan and his team at IBM were studying the photoluminescence from GaAs, trying a flash lamp for pumping, but were unsuccessful in achieving lasing.
- In Sep. 1962, they observed "**spectacular line narrowing**", the signature of lasing.
- Sent the results to *Applied Physics Letters*; the first real semiconductor laser at IBM was made in October 1962, and **the patent was issued in just five days**.
- Nathan and co-workers did not know Hall and co-workers (at General Electric) were also working on this and were shocked to learn Hall's APL paper had been submitted **11 days before** their own.
- This is a reminder of just **how exciting and fast-paced photonics research can be**.

M. Nathan. Source: AIP

Nature Photonics 6, 795 (2012)

In the beginning

- In the 60’ & 70’: diode lasers where “**a solution looking for a problem**”.

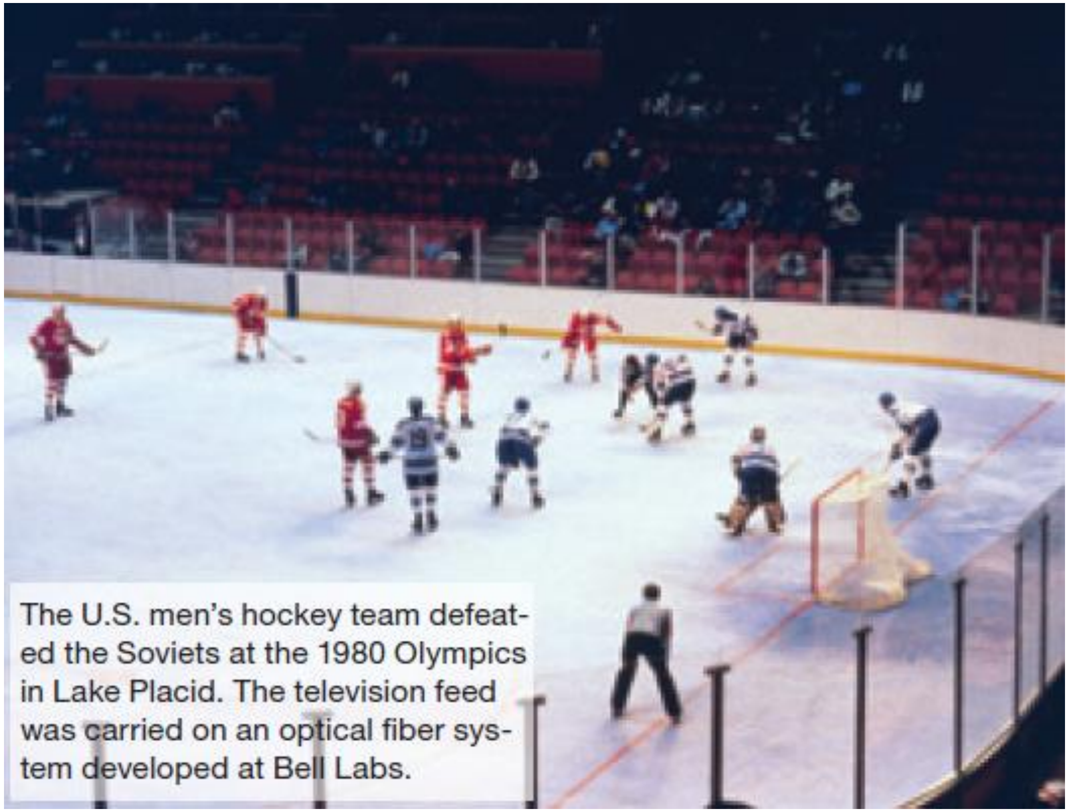


Source: laserfest.org

- Typically: 10–20 years from the initial proof-of-concept of lasing, often performed at low temperature, until devices useful for applications are obtained.
- Practical devices require continuous-wave (CW) operation at room temperature (RT), ideally with direct electrical pumping, and reasonably long lifetime.
- CW RT emission was achieved in **1970.**
- The performance of early diode lasers was limited by manufacturing techniques.

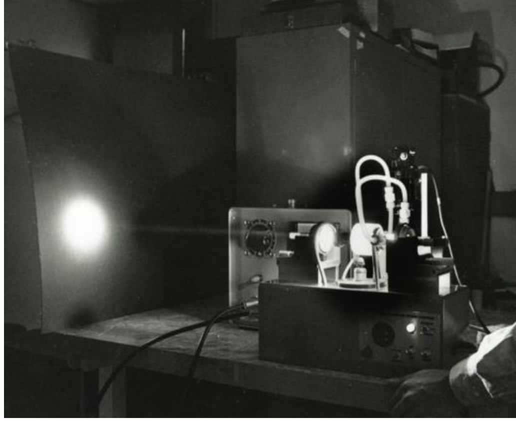
The first practical application

- February **1980**, an optical fiber system was used to **broadcast TV** (Winter Olympics, Lake Placid, US).



Source: Optics & Photonics News, May 2012

Energy efficiency



Flash-lamp-pumped dye laser (1968)

- Early CO_2 lasers converted 5-20% input electrical energy into laser light.
- Flash-lamp-pumped solid-state lasers 1%.
- HeNe 0.1%

- Argon-ion lasers 0.01%: 100 kW power generated 10 W beam while removing the waste heat required tens of liters of cooling water a minute.
- Things changed with the rapid development of diode lasers, which in the early 80s achieved 10% efficiency.
- Nowadays diode lasers can achieve 67% efficiency and high powers: single lasers can emit 100s Watts while diode laser arrays emit kWs.

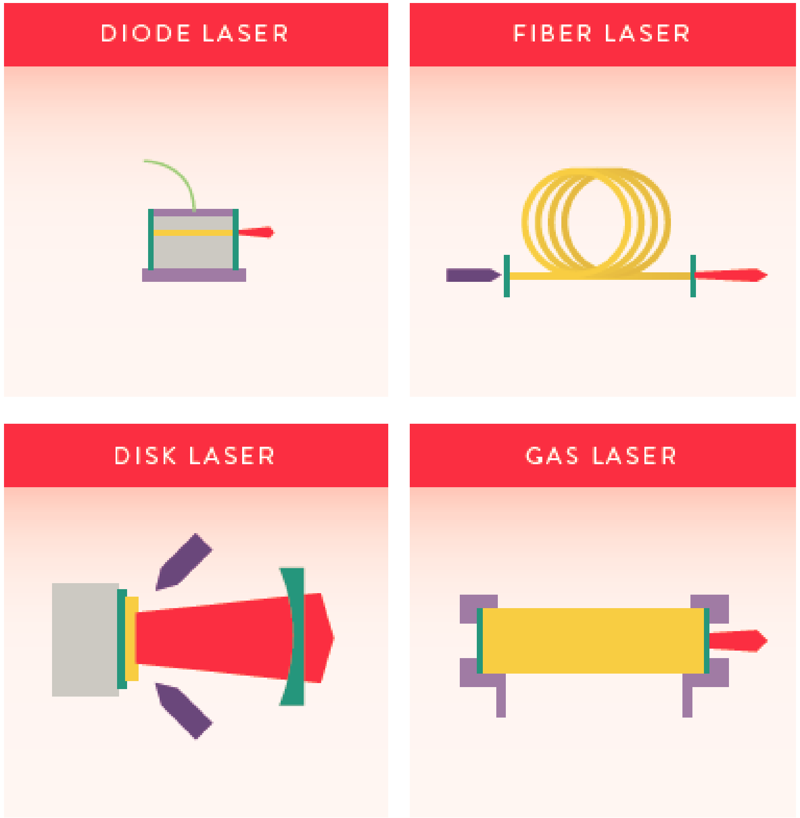
Source: Optics and Photonics News Oct. 2017

The first tunable laser

- Was demonstrated by Mary Spaeth (an engineer at Hughes Aircraft) in 1966.
- It used as gain medium organic dyes dissolved in organic solvents.
- Pumped with a ruby laser, laser pulses from dyes were emitted.
- The complex dye molecules sported broad gain bandwidths, and each had its own spectrum, which allowed a wide range of wavelengths.
- A year later, in 1967, Bernard Soffer and William McFarland (at Maiman's firm, Korad), took tunability further by replacing one mirror in the laser cavity with a *movable diffraction grating*.
- This tuned the dye emission across 40 nm while reducing its emission bandwidth by a factor of 100.

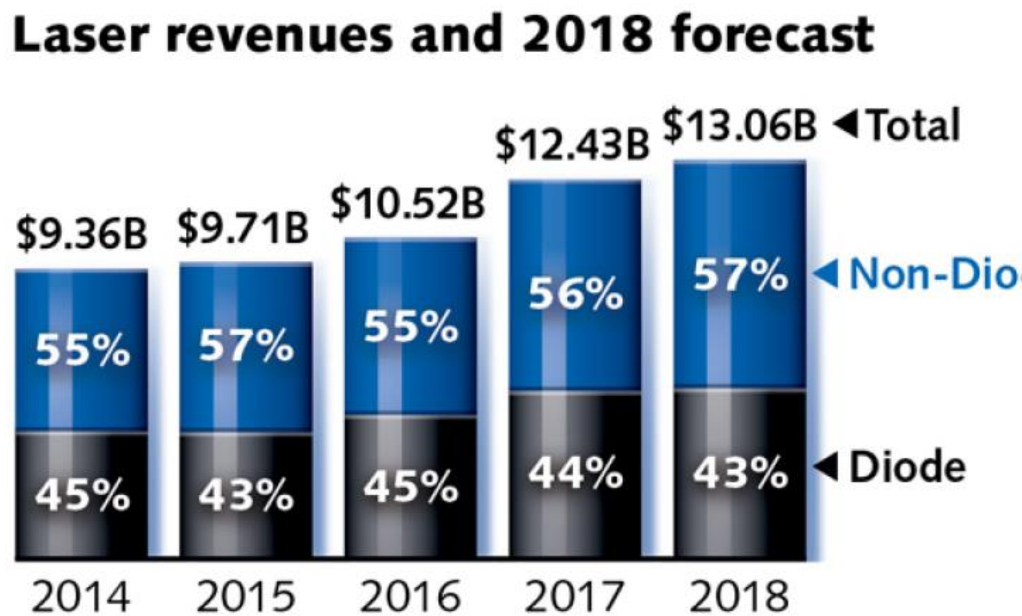
Source: Optics and Photonics News Oct. 2017

Over the last 50 years, many different lasers have been fabricated



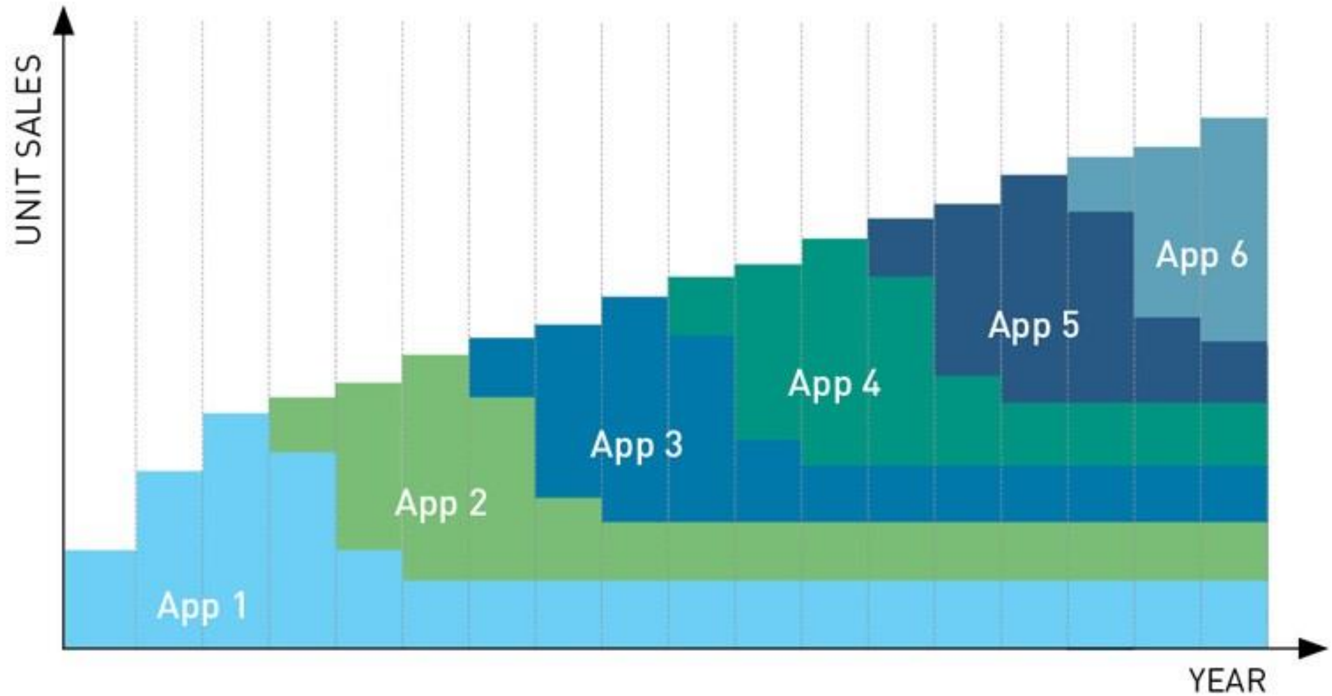
Further Reading: www.light2015.org
https://www.lightday.org/ (16 of May)

After more than 50 years, diode laser-enabled technologies are big business



Source: Laserfocusworld.com

Laser Market's Long-Term Growth



Due to

- The gradual expansion of the global economy .
- After 50 years of growth the major laser applications are established and each "new niche" adds a smaller, incremental share to the overall market—but the many increments add up.

Source: Optics and Photonics News Oct. 2017

Main application of diode lasers: optical communications

No diode laser $\Rightarrow$ No internet!

Source: Infinera

LIDAR: one of the hottest technologies

- Light detection and ranging (LIDAR) is becoming ubiquitous.
- In 2 to 3 years the technology went from Google-car curiosity to mainstream driver-assist implementation.
- In 2016 Uber acquired a self-driving technology company and is planning to replace its 100 million human drivers with robot drivers.

- The LIDAR technology is becoming **cheap** enough and **reliable** enough for implementation on a commercial scale.
- Next: self-driving trucks.

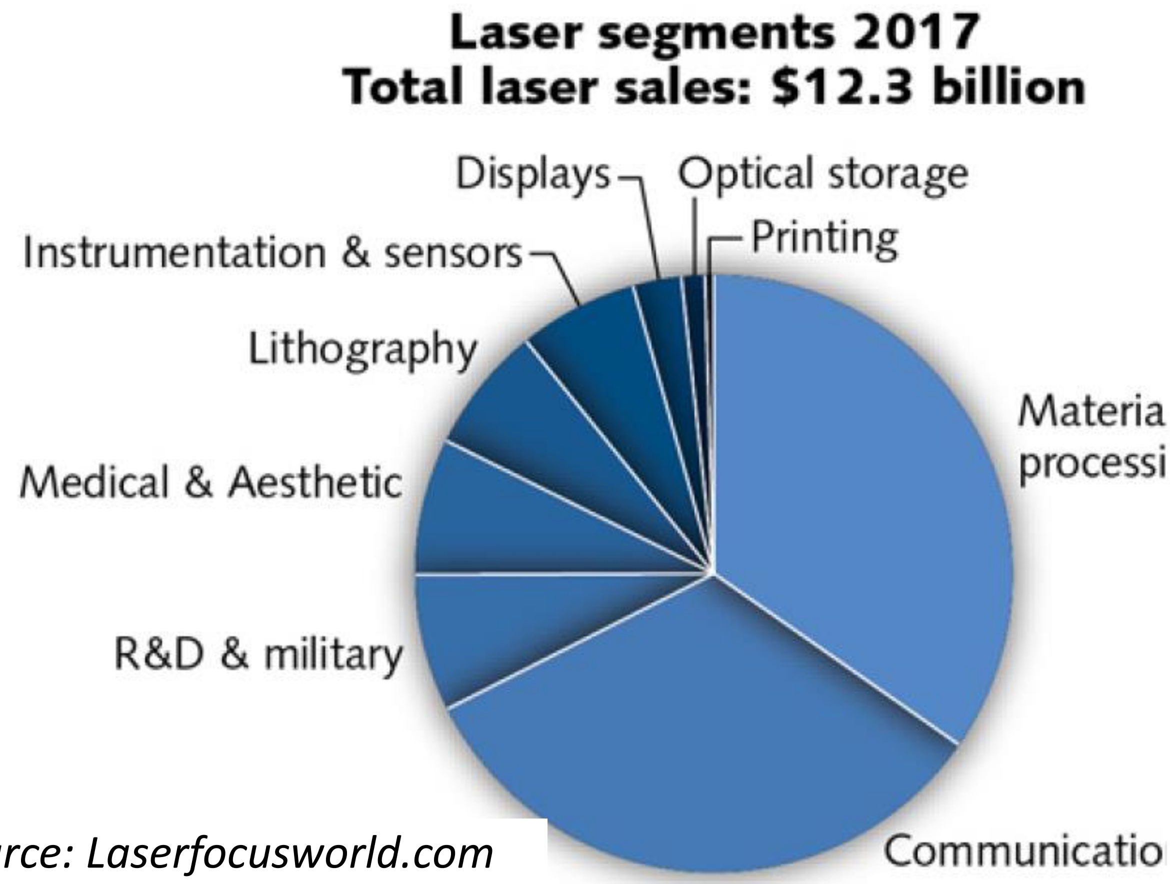
Other hot applications enabled by lasers

- As the world population continues to age, the need for **medical lasers** continues to grow.

- Automation and 'smart' technologies require more laser-based **sensors** and 3D-printed components.

- Internet of Things (IoT) and digital communications increase the need of **telecom** lasers and lasers for **lithography** technologies.

Laser market segments (all lasers)

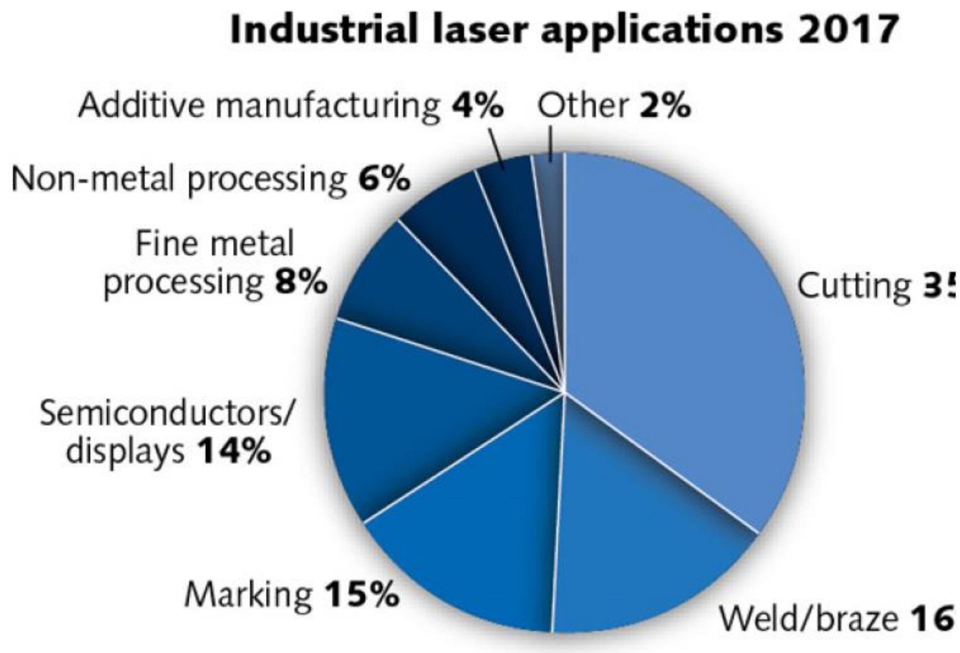


Source: Laserfocusworld.com

Increased reliability and huge price reduction made possible these applications.

Industrial lasers
materials processing & lithography

- Automotive, aerospace, energy, electronics, and smartphones.
- Lasers for all types of material processing
  – welding,
  – cutting,
  – marking,
  – additive manufacturing



- Excimer laser lithography: enables the semiconductor industry to create structures the size of a virus on a chip.

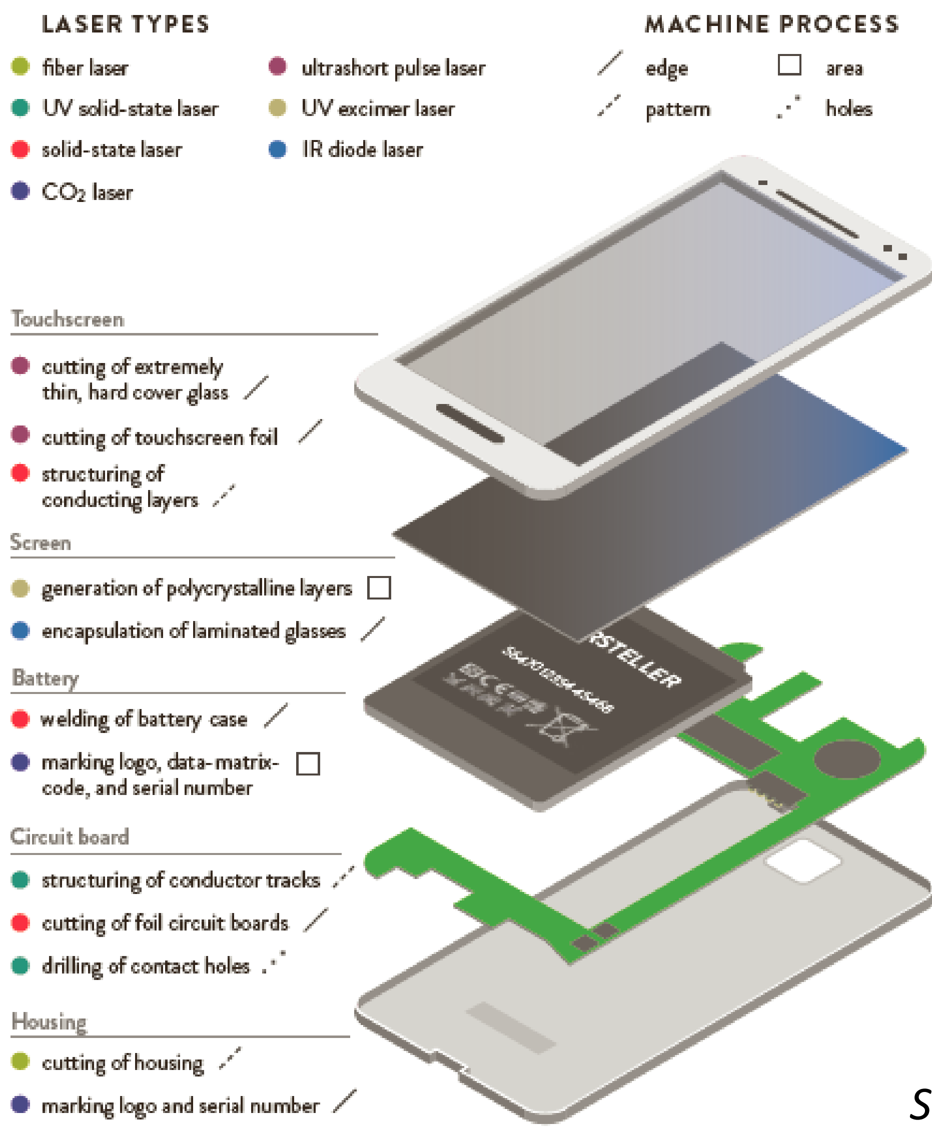
Extreme Ultraviolet (EUV) Lithography

- While minimum feature size achieved on chips in 2016 is 10 nm (the cold virus is twice as large), with EUV lithography chips with 5 nm features are expected in near future.
- This means faster, cheaper and more energy efficient smartphones, computers, etc.

The first photo taken with a mobile phone (P. Kahn 1997)

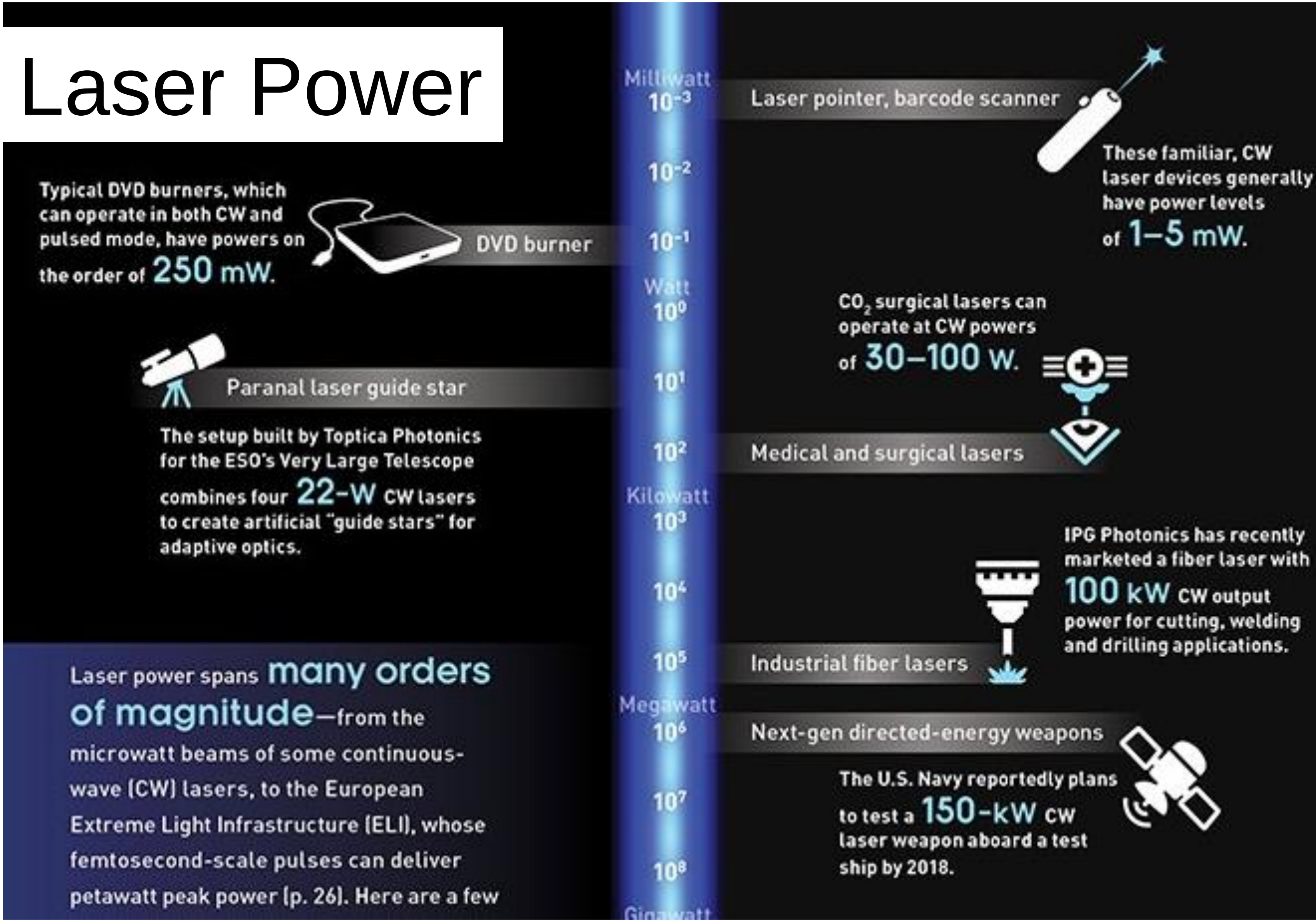
Internet of Things (IoT)

SMARTPHONES: thanks to the laser



Source: SPIE

Laser Power



ELI-Beamlines laser: peak power > 1 Petrawatt = 10^{15}

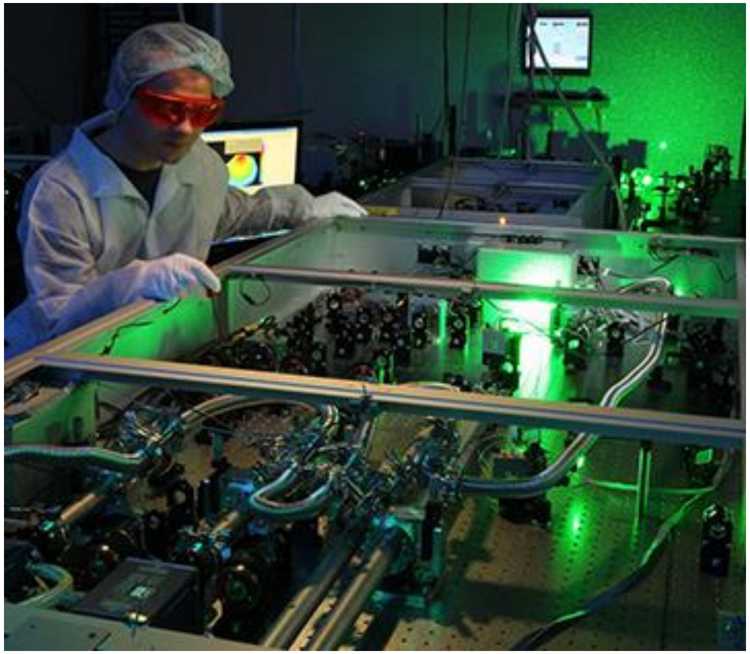
Source: Optics and Photonics News, October 2017

Extreme Light

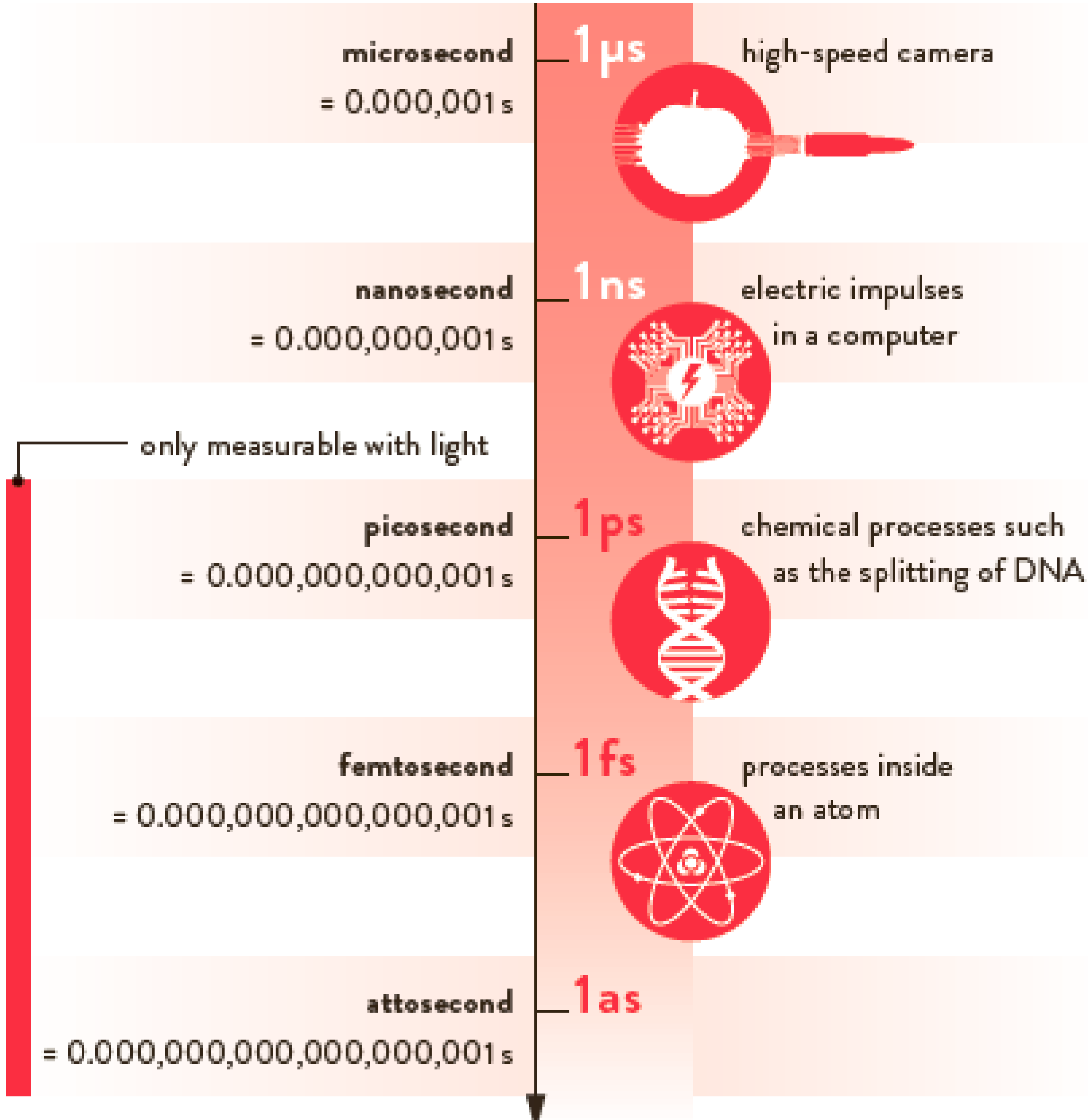
Ultrafast lasers (pulse width in the femto and attosecond range) generate extremely energetic pulses that allow building a **table top version of a synchrotron**.

A consortium led by two Lithuanian firms has built a **5 TW (10^{12})** optical parametric amplifier (OPA) system for the European Extreme Light Infrastructure (ELI).

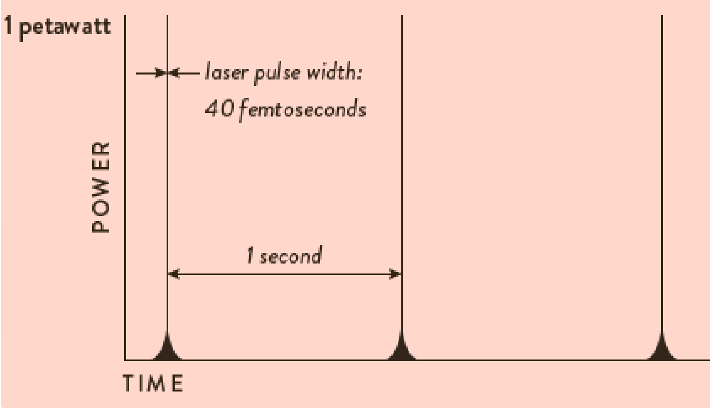
Source: Optics and Photonics News 10/17



Femto and attosecond pulses



Generated power of the Berkeley Lab Laser Accelerator
1 petawatt
= 1,000,000 gigawatts



Source: SPIE

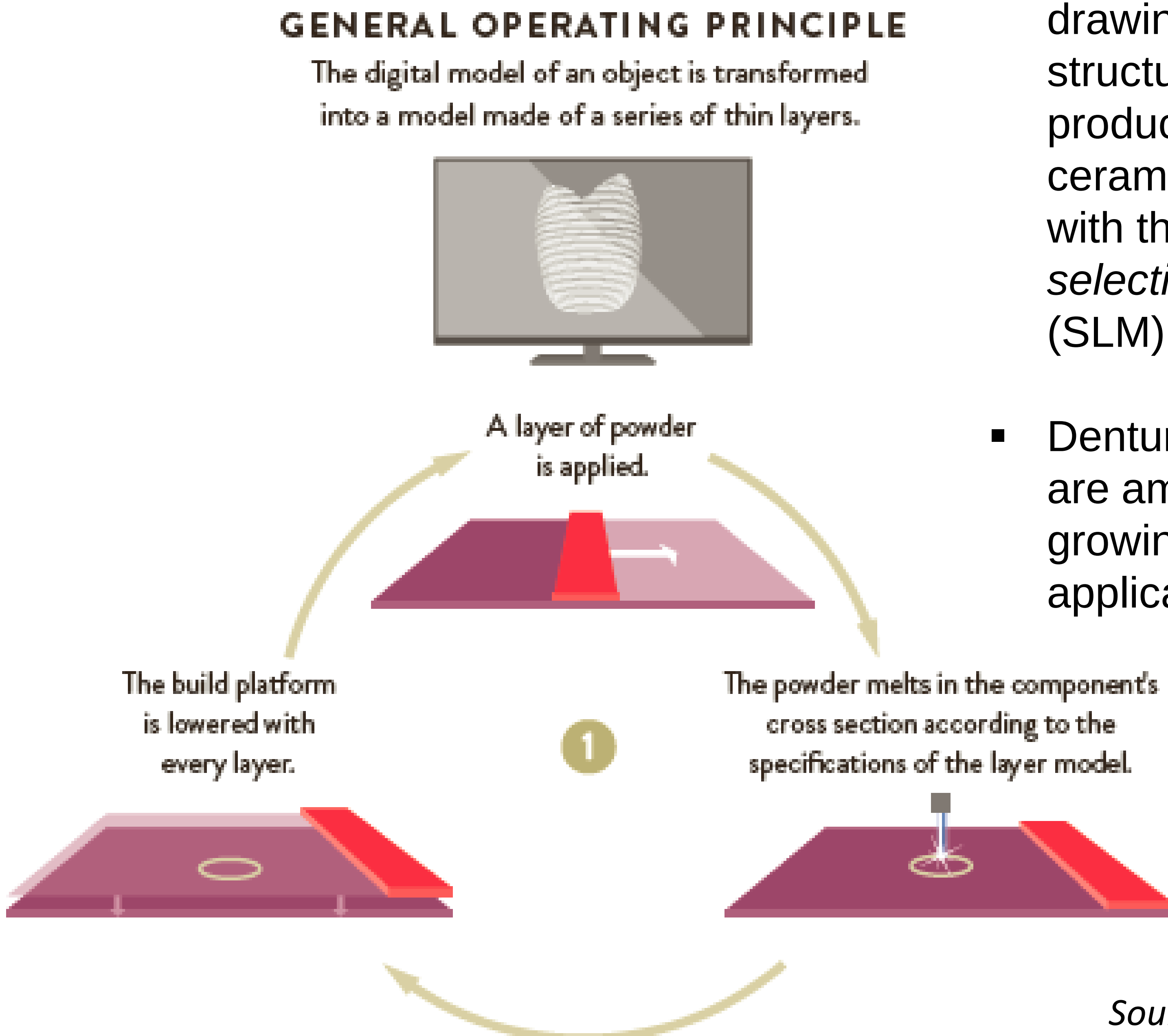
Additive manufacturing (AM)

- Also known as **3D printing** and **rapid prototyping**

- AM covers a broad family of technologies that join material progressively, layer upon layer, to make finished objects using an additive approach.

- This is opposed to traditional subtractive manufacturing techniques, in which material is removed from a larger structure in order to arrive at a completed item.

- AM has advanced to the point where it is **moving from a rapid prototyping tool to a rapid manufacturing tool**.



- Based on a computer drawing, complex structures can be produced from plastics, ceramics, and metals with the help of *selective laser melting* (SLM).

- Dentures and implants are among the rapidly growing number of applications.

Source: SPIE

Key 3-D sectors





	Aerospace	Medical	Automotive	Electronics	Consumer use
MATERIALS	▸ Titanium, high-performance thermoplastics, stainless steel, CFRP, GFRP, nickel alloys, cobalt-chrome	▸ High-performance thermoplastics, titanium, stainless steel	▸ Steel, stainless steel, magnesium, thermoplastics	▸ Thermoplastics, functional materials	▸ Thermoplastics, paper
USE	▸ Engine components, brackets, connectors	▸ Implants, prosthetics	▸ Interior components, aesthetic components, body panels	▸ Embedded electronics, smart objects, sensors, conductive traces	▸ Art, architectural models, replacement parts

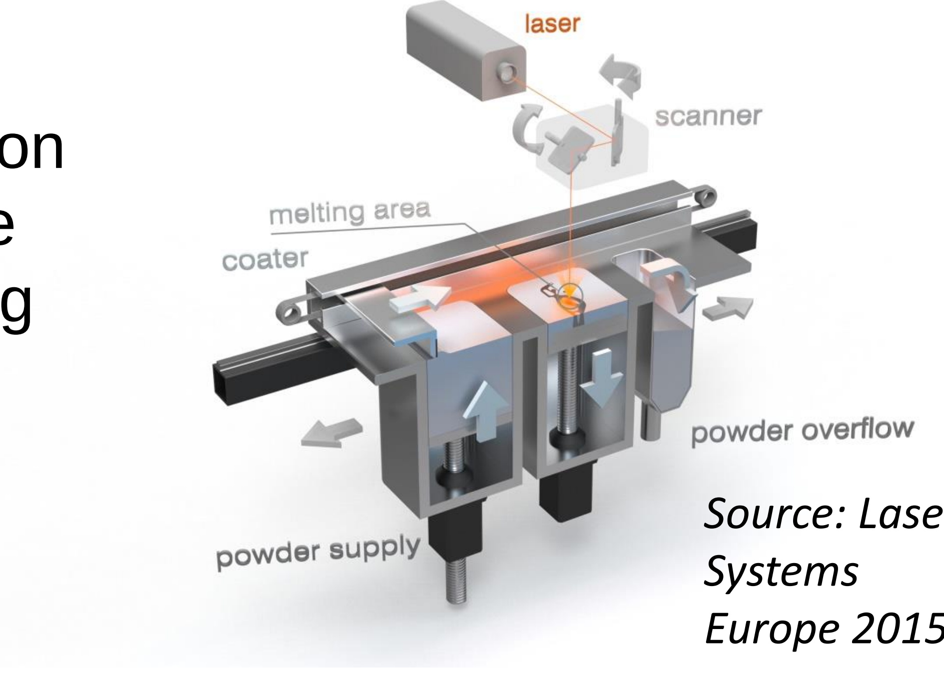
Technology	Description	Applicable Materials
Stereolithography	Selectively cures a uniform layer of material with a UV laser	Photopolymers
Digital light processing	Cures an inkjet-deposited material layer in a support material with a UV light	Photopolymers
Polyjet	Cures an inkjet deposited layer with multiple materials using a UV light	Photopolymers
Selective layer sintering	Selectively fuses material powder using a laser	Thermoplastics, metals

Source: Optics and Photonics News, august 2013

Costs?

- Still high!
- Example: selective laser melting (SLM) machine (cost €1.5 million) was used to produce a prototype V8 engine block for an automotive company. Despite the expense, the SLM machine cut the time to manufacture the prototype from months to weeks.

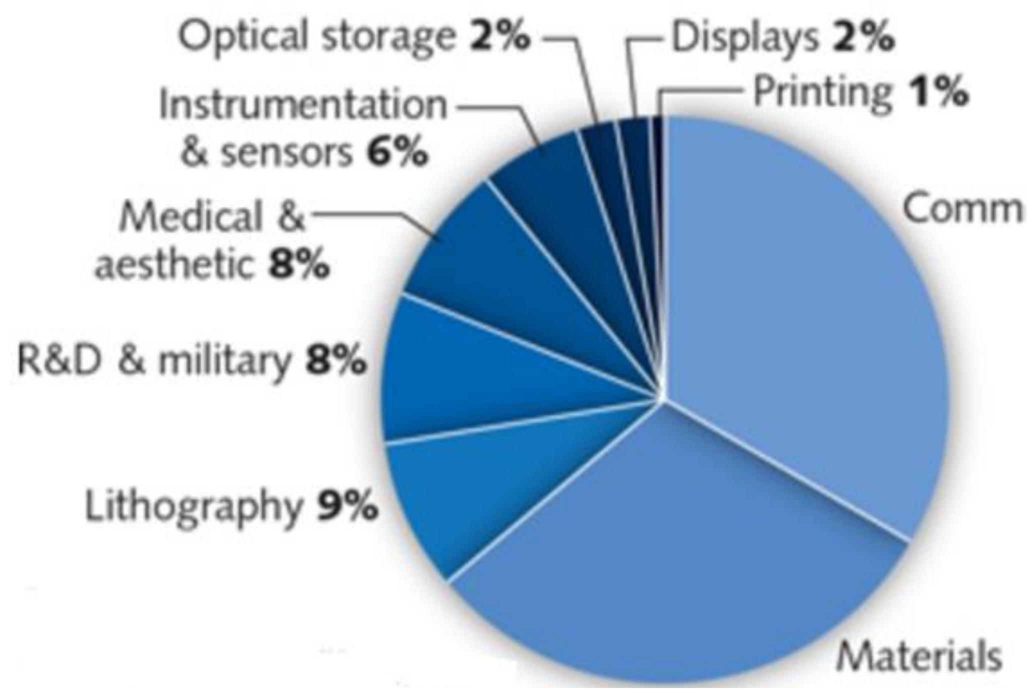
- With a SLM system based on diode lasers, the cost of the machine and the processing could be lowered dramatically.



Source: Laser Systems Europe 2015

The other laser market segments

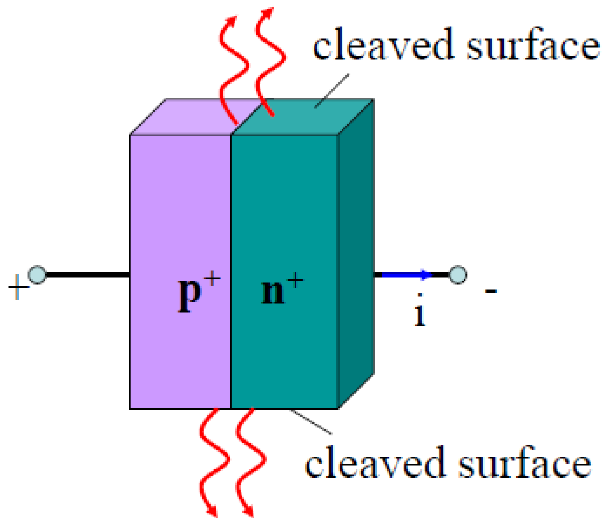
- **Communications:** all laser diodes used in telecom, datacom, including **pumps** for amplifiers used in long-distance fiber-optic links.
- **Optical storage** (DVD, CD, and Blu-ray media): decreasing due to cloud-based solutions that are eliminating the need for large local storage.



- **Medical & aesthetic:** lasers used for ophthalmology, surgical, dental, therapeutic, skin, etc.

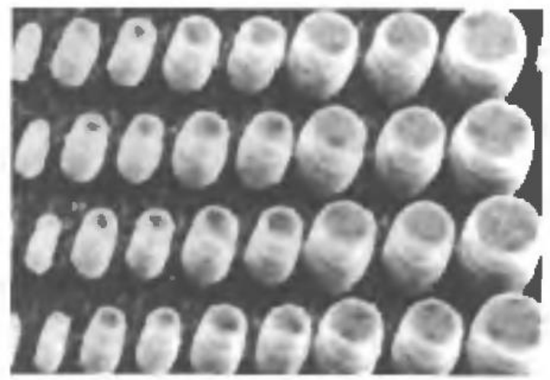
Why diode lasers are so popular?

- **Low cost** because of **existing** semiconductor technology.
- Do not require fragile enclosures or mirror alignment: the sharp refractive index difference between the semiconductor material (~3.5) and the surrounding air causes **the cleaved surfaces to act as reflectors**.
- **Electrically pumped.**
- **High efficiency.**
- Bright output considering their small size.



Why diode lasers are so popular?

- For telecom and datacom: can be **modulated at high speed**.
- Semiconductor materials provide a **wide range of wavelengths** (mid IR to UV). In particular, in the infrared regions where silica optical fiber has minimum dispersion or transmission loss.
- Easy integration in 1D & 2D arrays.
- High powers can be obtained (kWs) thanks to new **wavelength combiners** that convert multiple diode wavelengths into very high energy, high-quality beams.



VCSELs with diameters 1- 5 μm.
Adapted from Saleh and Teich

- A drawback: vulnerable to voltage fluctuations such as transients and electrostatic discharge.

Outline

- Introduction
- **Semiconductor materials**
- Photons in semiconductors
- Semiconductor light sources
  - LEDs
  - Amplifiers
  - Semiconductor lasers

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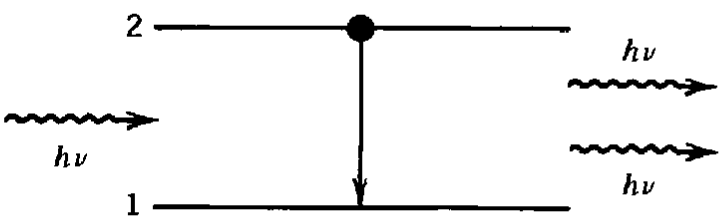
Bibliography: *Fundamentals of Photonics*, B.E.A. Saleh and M.C. Teich

Band structure and pn-junctions

- In semiconductors the bandgap between CB and VB is smaller than in an isolator (~1eV).
- *Intrinsic*: the semiconducting properties occur naturally.
- *Extrinsic*: the semiconducting properties are manufactured.
  - **Doping**: the addition of 'foreign' atoms.
    - **N-type**: has an excess of electrons.
    - **P-type**: shortage of electrons (excess of 'holes')
  - **Junctions**: join differing materials together ("compound" semiconductors).
- *Direct*: light sources
- *Indirect*: photo-detectors

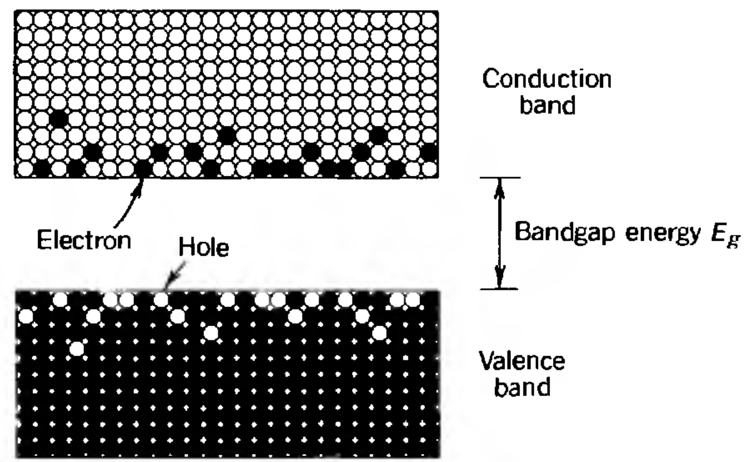
2-level vs. semiconductor material

In a 2-level system: non interacting particles & individual energy levels



For lasing we need population inversion:
$N_2 > N_1$

In a semiconductor: electron/hole pairs & energy bands

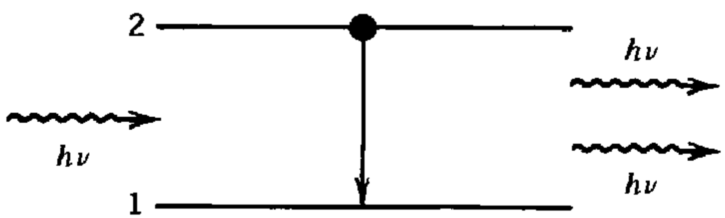


For lasing we need a large enough concentration of electrons in the CB and holes in the VB

Charge neutrality:
$N_e \approx N_h \approx$ **N carrier concentration**

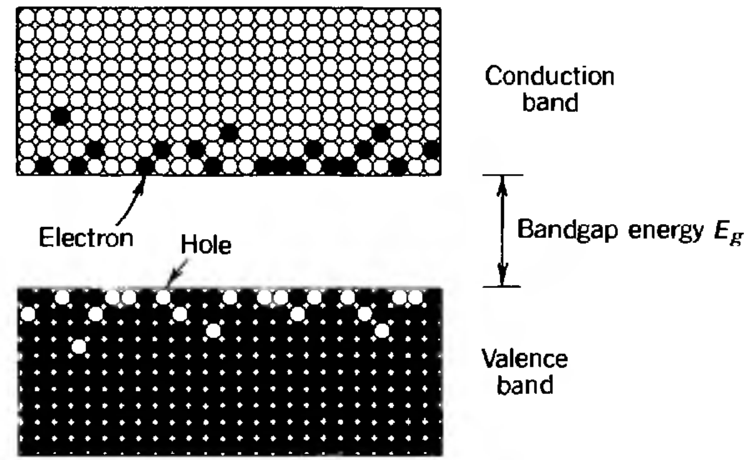
2-level vs. semiconductor material

In a 2-level system:



A particle in an excited state decays emitting a photon

In a semiconductor:



A pair electron/hole recombine emitting a photon; λ depends on E_g

$\nu_g = E_g/h$, $\lambda_g = c/\nu_g \Rightarrow \lambda_g = hc/E_g$

$$\lambda_g = \frac{1.24}{E_g}$$ λ_g (μm) and E_g (eV)

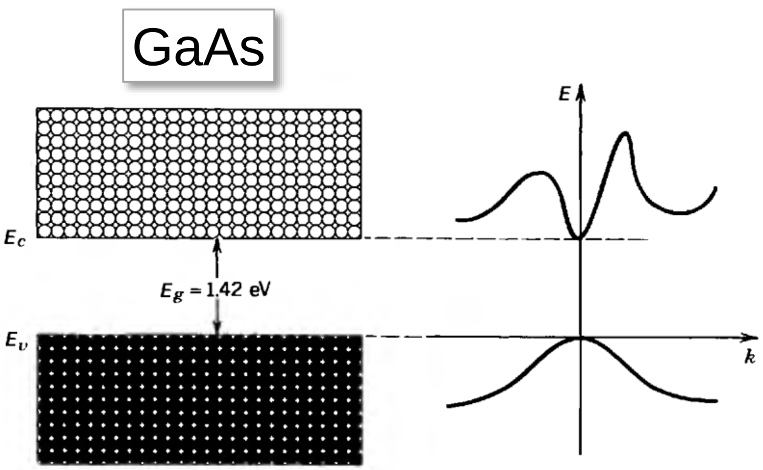
Conservation of momentum: $p_e \approx p_h$ ($p_{photon} \approx 0$) $\Rightarrow k_e \approx k_h$

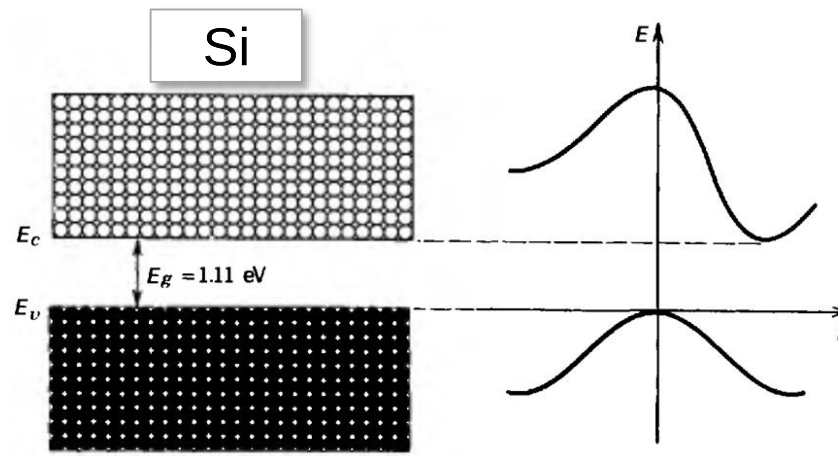
$\Rightarrow$ Optical transitions are **vertical** in k space

Energy - momentum relation

Near the bottom/top of the conduction/valence bands:

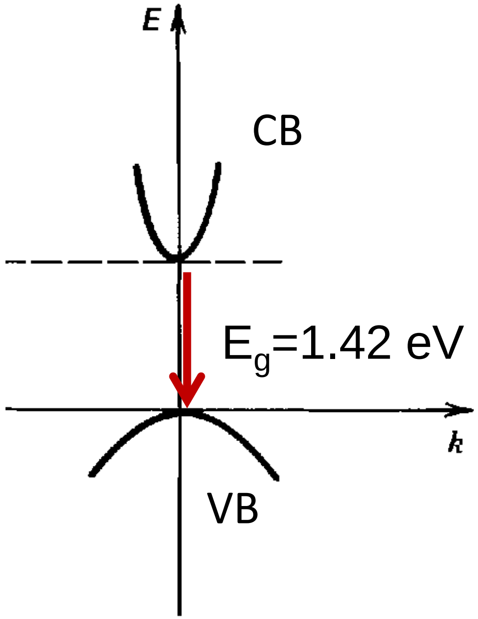
$$E = E_c + \frac{\hbar^2 k^2}{2m_c} \qquad E = E_v - \frac{\hbar^2 k^2}{2m_v}$$

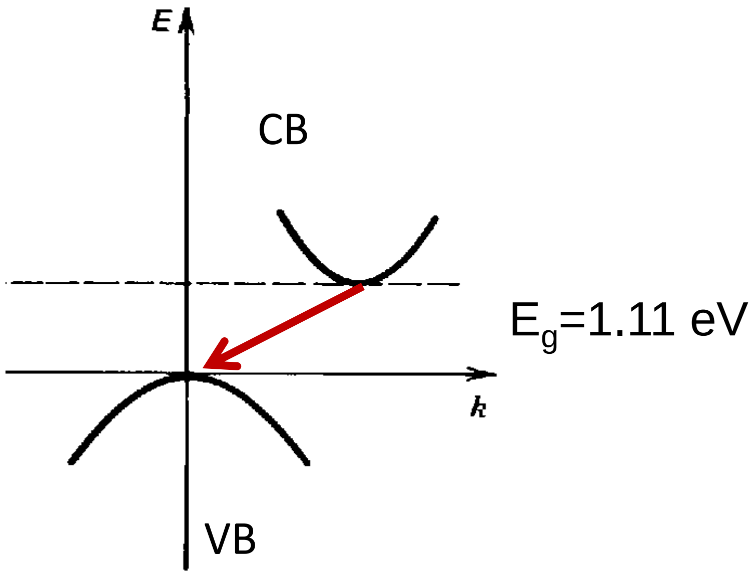




Gallium arsenide

Direct and indirect semiconductors

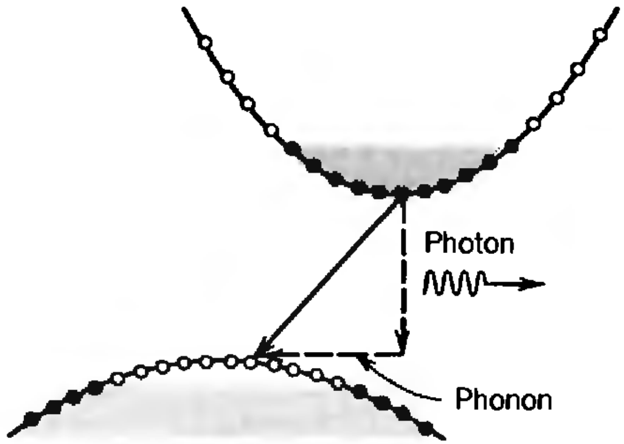


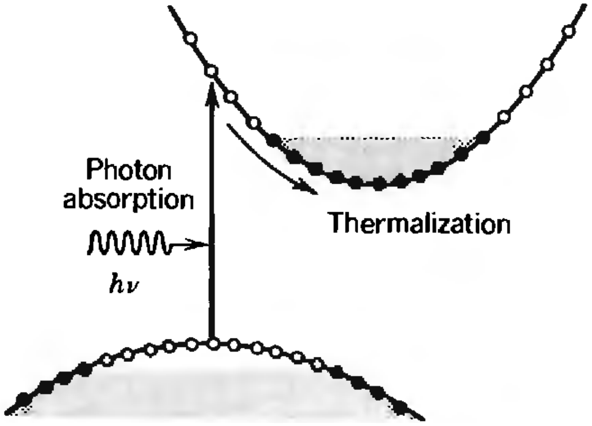


Direct optical transitions (GaAs) efficient photon sources

Indirect optical transitions (Si, Ge) inefficient photon sources (but efficient photo-detectors)

Indirect semiconductors (Si, Ge)





The energy can be carried off by one photon, but one or more phonons (lattice vibrations) are required to conserve momentum. Simultaneous **multi-particle interactions unlikely**.

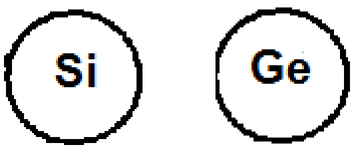
Photon absorption is a **sequential, two-step process** (first absorb photon energy, then momentum transferred to phonons). Thus, is not unlikely.

Semiconductor materials

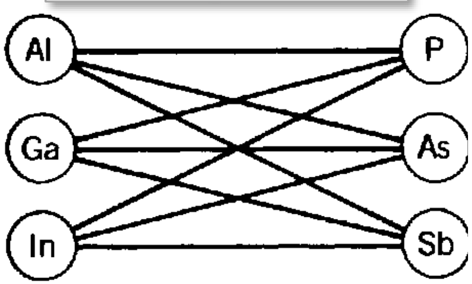
III		IV		V	
Aluminum	(Al)	Silicon	(Si)	Phosphorus	(P)
Gallium	(Ga)	Germanium	(Ge)	Arsenic	(As)
Indium	(In)			Antimony	(Sb)

Compound semiconductors: by combining different semiconductors, materials with different optical properties (λ_g, refractive index) can be fabricated.

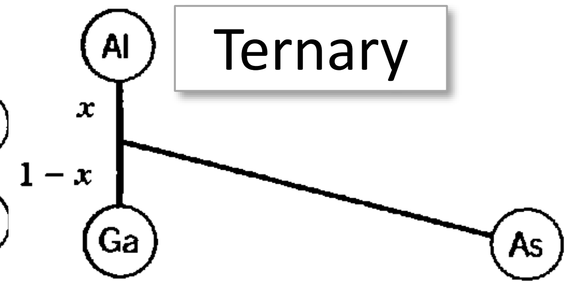
Elementary



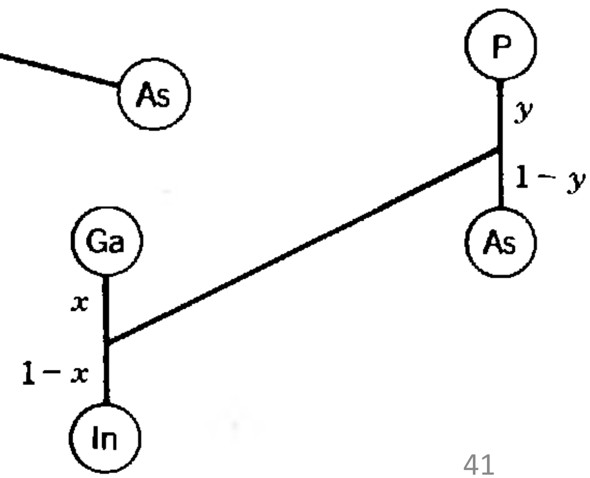
Binary: III - V



Ternary



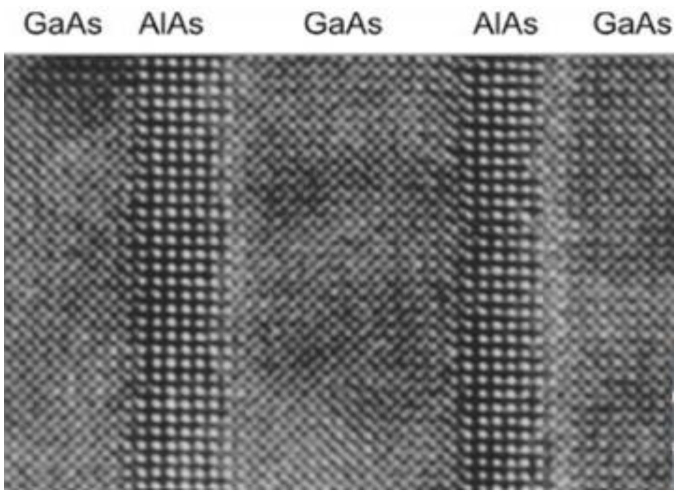
Quaternary



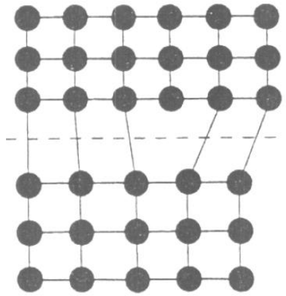
Almost all the III–V semiconductors can be used to fabricate lasers

Lattice constant

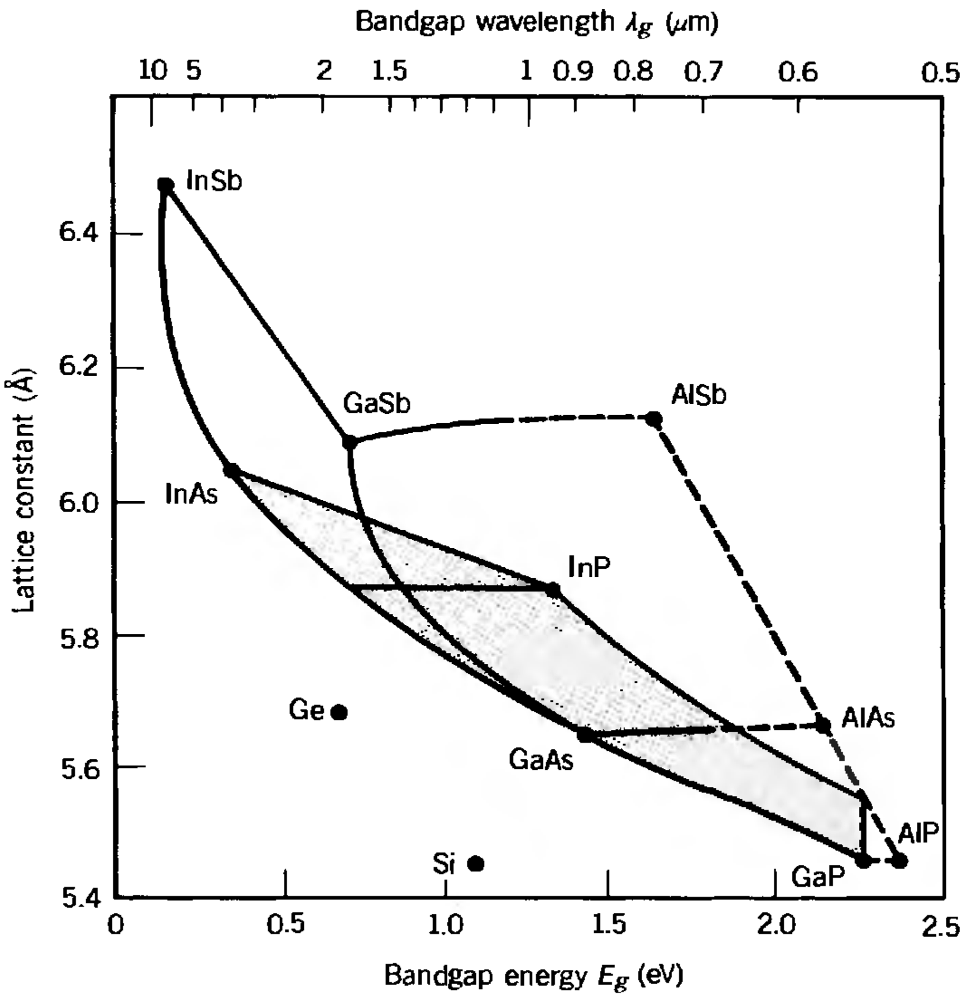
- By adjusting the composition of the compound material, its lattice constant can be adjusted to match that of the substrate.
- This is important because
  - A good lattice match allows to grow high-quality crystal layers.
  - Lattice mismatch results in crystalline imperfections which can lead to nonradiative recombination.
  - Lattice mismatch reduce the laser lifetime.



from Infinera



Binary compounds



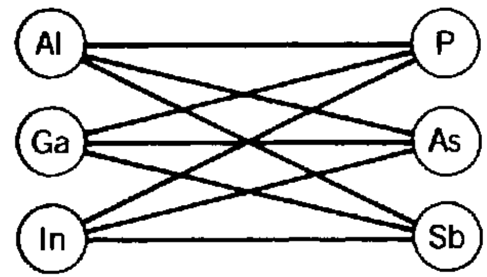
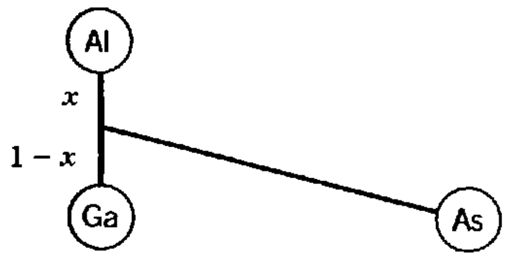


TABLE 15.1-3 Selected Elemental and III–V Binary Semiconductors and Their Bandgap Energies E_g at $T = 300$ K, Bandgap Wavelengths $\lambda_g = hc_o / E_g$, and Type of Gap (I = Indirect, D = Direct)

Material	Bandgap Energy E_g (eV)	Bandgap Wavelength λ_g (μm)	Type
Ge	0.66	1.88	I
Si	1.11	1.15	I
AlP	2.45	0.52	I
AlAs	2.16	0.57	I
AlSb	1.58	0.75	I
GaP	2.26	0.55	I
GaAs	1.42	0.87	D
GaSb	0.73	1.70	D
InP	1.35	0.92	D
InAs	0.36	3.5	D
InSb	0.17	7.3	D

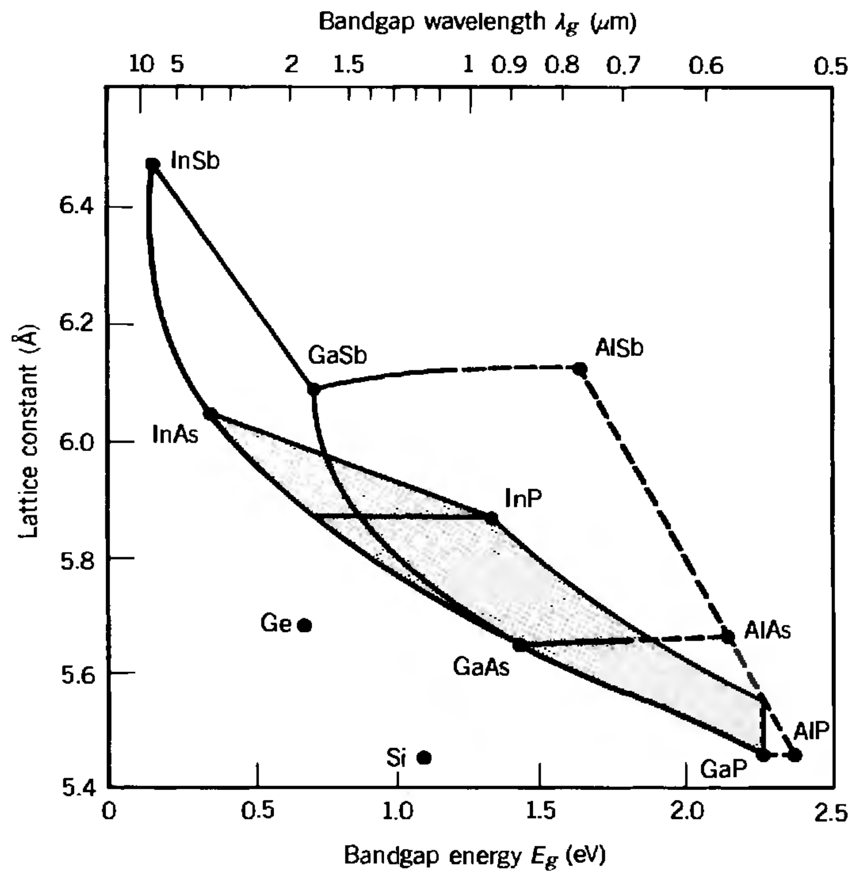
Ternary compounds



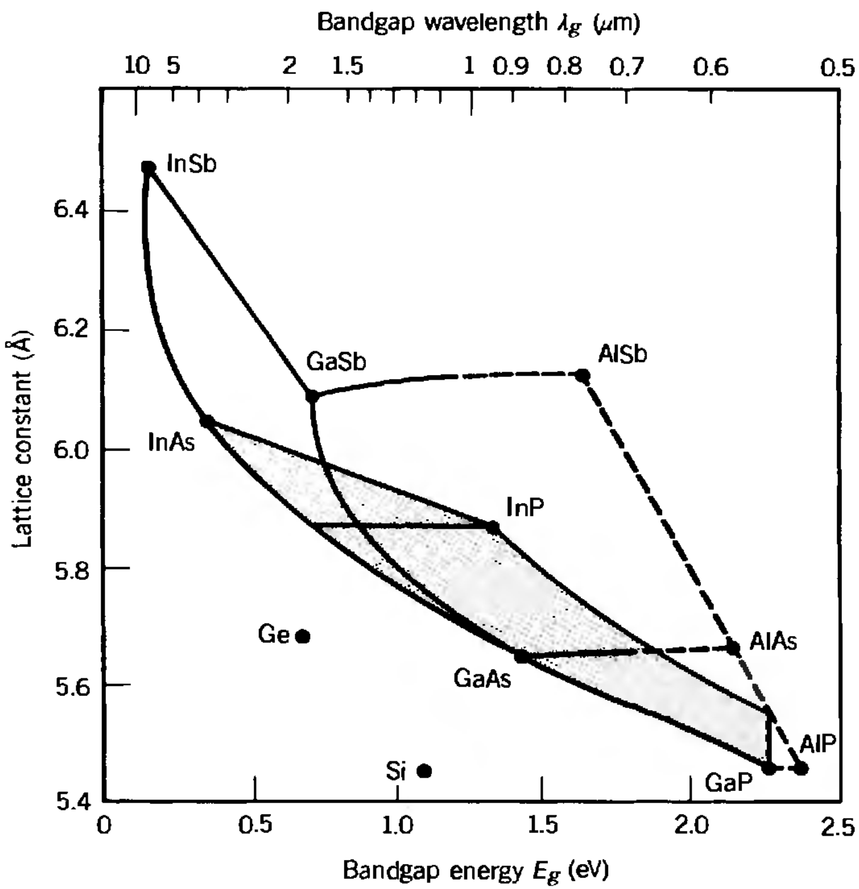
- 2 III + 1 V or 1 III + 2 V
- Formed by moving along the lines (solid/dashed = direct/indirect material)

- GaAs $\rightarrow$ AlAs as x=0 $\rightarrow$ 1

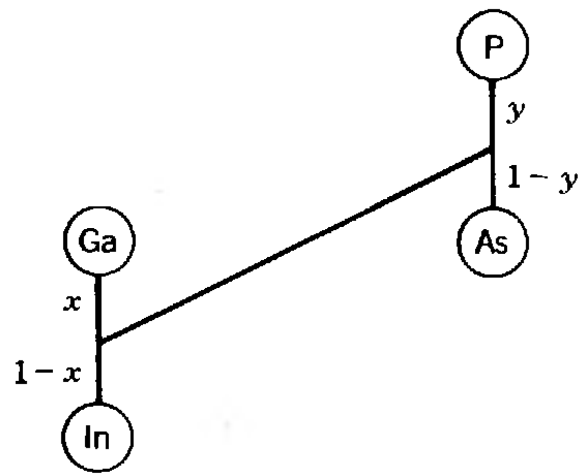
A nearly horizontal line is important: it means that a layer of one material can be grown on a layer of another material.



Quaternary compounds



A quaternary compound is represented by a point inside the area formed by the 4 components.

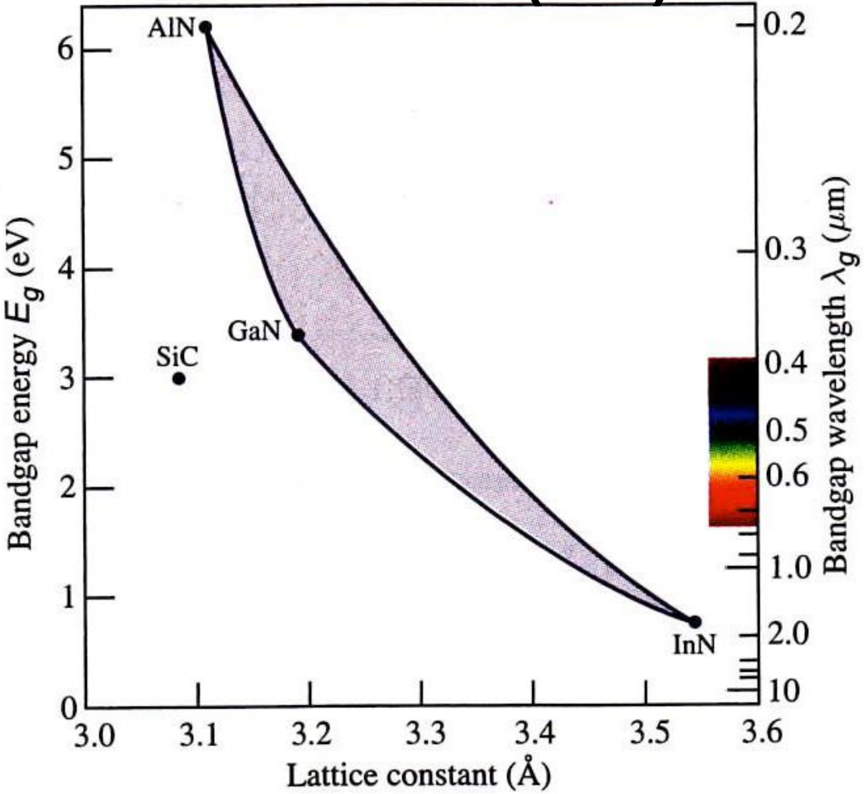


"y" : is an extra degree of freedom that allows to adjust both, the lattice constant and the band-gap

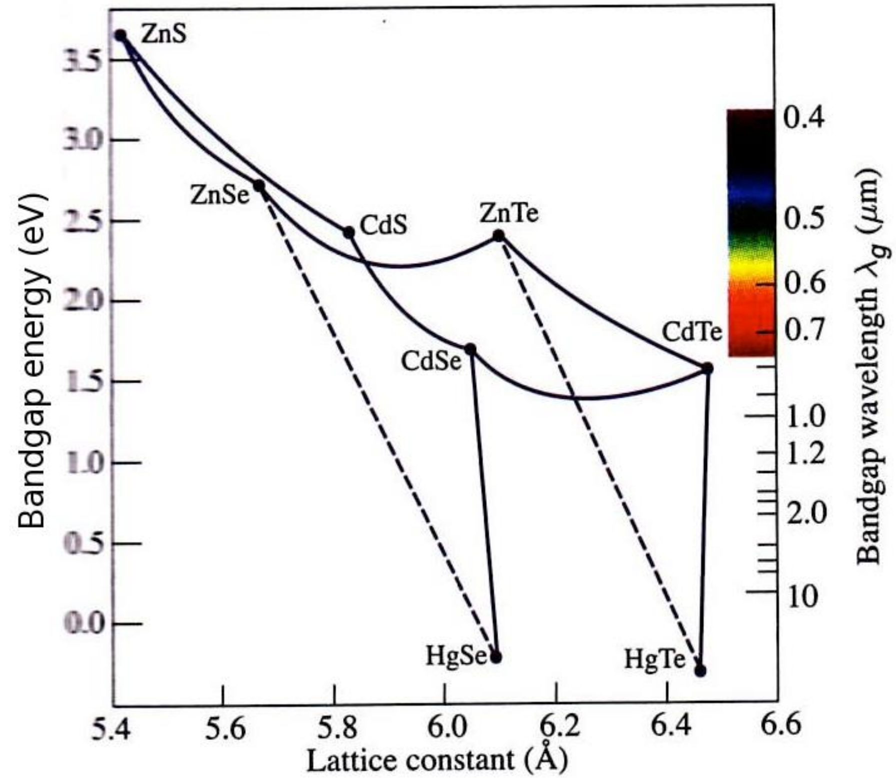
The shaded area represents the range of (band-gap, lattice constant) spanned by the compound **$(In_{1-x}Ga_x)(As_{1-y}P_y)$**.

Semiconductor materials for blue and green light sources

Gallium nitride (GaN)



Zinc selenide (ZnSe)



Other popular option: Zinc Oxide (ZnO), a direct semiconductor

Materials and wavelengths

- **UV and blue (445 - 488 nm):**
  - First developed in the 1990s (more latter)
  - GaInN
  - Increasing indium increases wavelength
  - Applications: Blu-rays (405 nm); LED lighting (460 nm); life sciences
- **Green (515-525 nm):**
  - III-V materials: InGaN on GaN
  - II-VI diodes: ZnSe
  - Applications: pico-projectors, life sciences
- **Red (625-700 nm):**
  - $Al_yGa_xIn_{1-x-y}P/GaAs$
  - Al concentration decreases wavelength
  - Applications: DVD (650 nm); pointers (635 nm); scanners (635 nm)

Infrared: materials and wavelengths

- GaAlAs: 750-904 nm
  - Al decreases wavelength
  - Applications: CD players, high-power uses

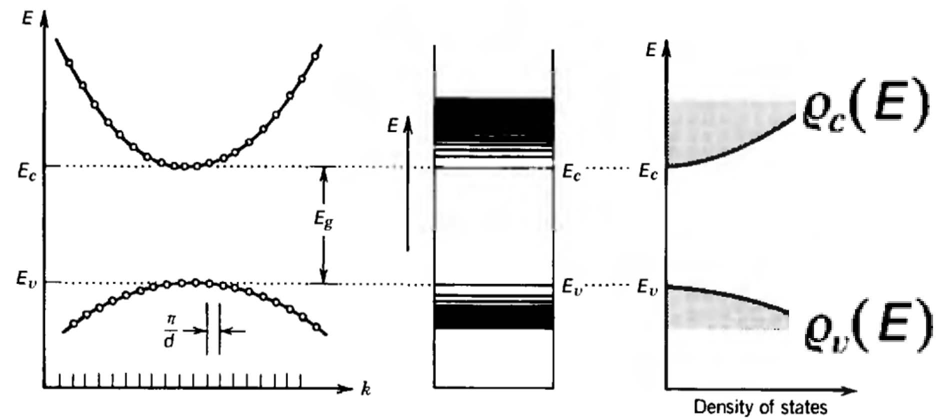
- InGaAs/GaAs: 915-1050 nm
  - In increases wavelength
  - Applications: pump lasers (915 nm Yb-fiber; 940 nm Er, Yb; 980 nm Er-fiber)

- InGaAsP/InP: 1100-1650 nm
  - First quaternary diodes
  - Applications: fiber-optic communications

Optical properties of semiconductors

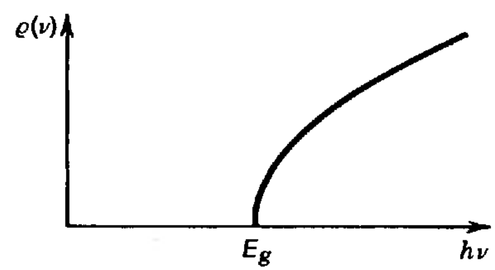
- The gain, the absorption coefficient, and the refractive index depend on the electron/hole concentrations.
- Electron/hole concentration can be calculated from
  - The density of states
  - The probability of occupancy

- <u>Density of states</u> of a "bulk" material (parabolic bands; more latter about non-bulk materials such as QWs and QDs).

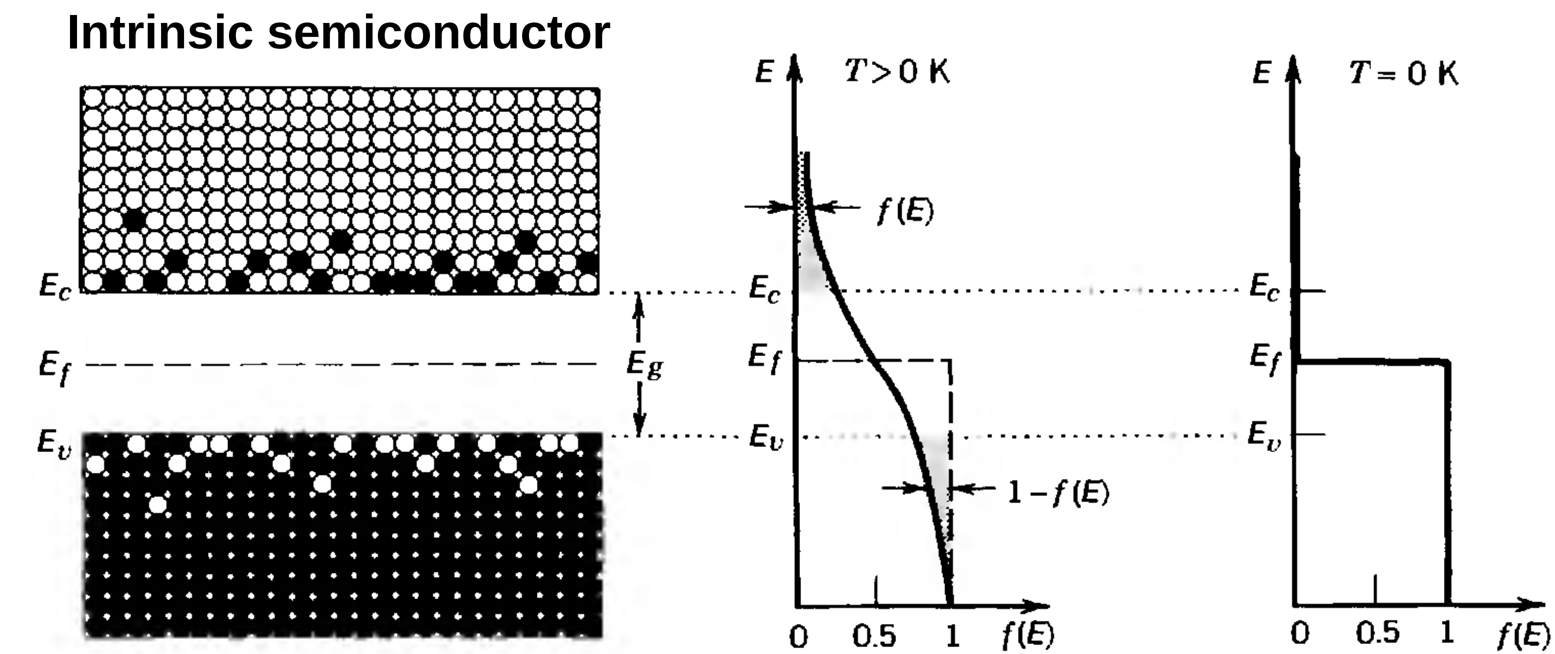


- <u>Joint density of states</u> [$m^{-3}Hz^{-1}$]

$$\varrho(\nu) = \frac{(2m_r)^{3/2}}{\pi\hbar^2}(h\nu - E_g)^{1/2}, \qquad h\nu \geq E_g$$



Probability of occupancy



$f(E)$ = probability of occupancy by an electron

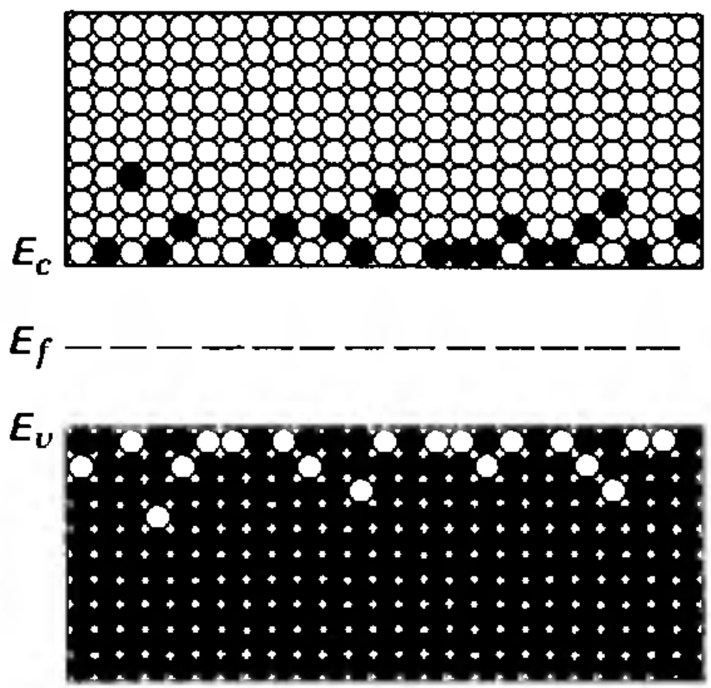
$1 - f(E)$ = probability of occupancy by a hole (valence band).

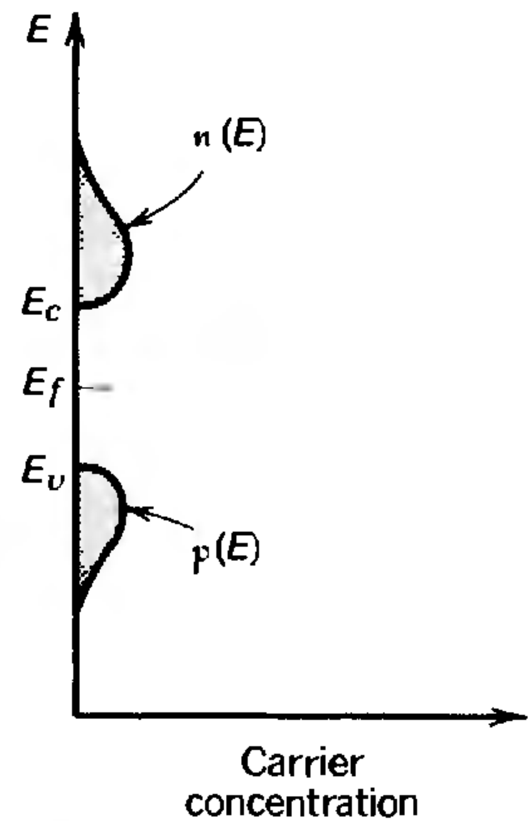
$$f(E) = \frac{1}{\exp\left[(E - E_f)/k_B T\right] + 1}$$ Fermi Function

Carrier concentrations in thermal equilibrium

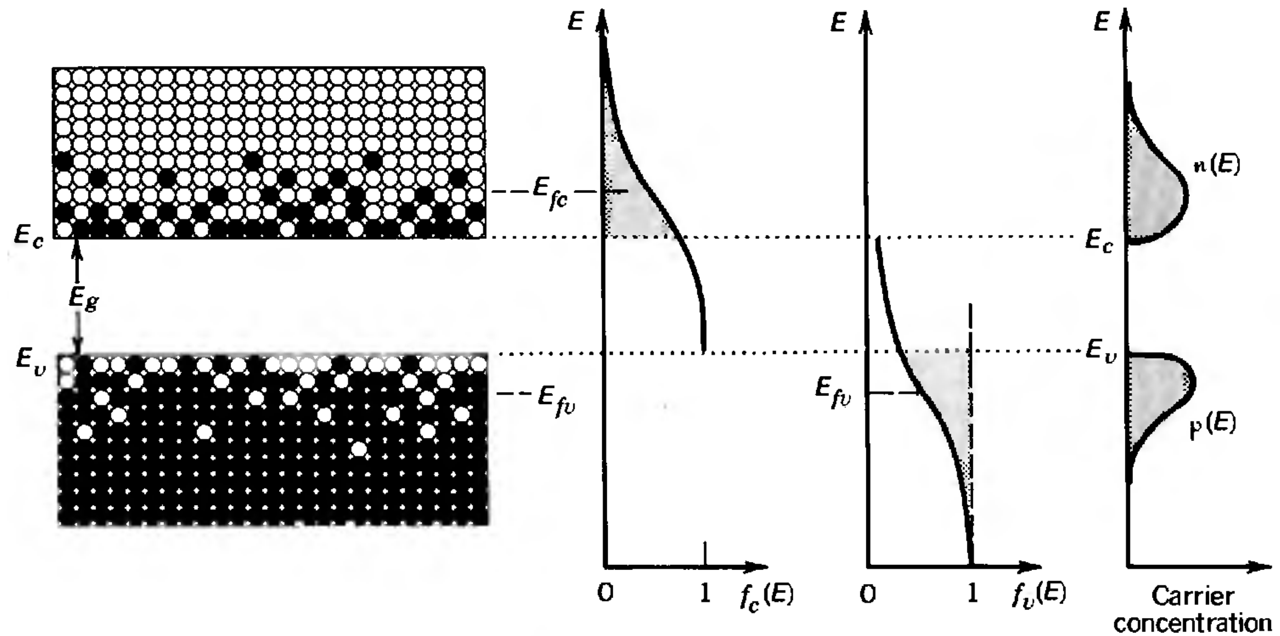
$$n(E) = \varrho_c(E) f(E), \qquad p(E) = \varrho_v(E)[1 - f(E)]$$

Same
Fermi level





Quasi-equilibrium carrier concentrations



- The **intra-band relaxation time** (ps) is much faster than **inter-band relaxation time** (ns).
- When electrical current or photon flux induces band-to-band transitions, the electrons in CB (and the holes in VB) are thermal equilibrium among themselves, but they are not in mutual equilibrium: **quasi-Fermi levels** (E_{fc} , E_{fv}) describe each concentration.

Absorption and emission probabilities

Emission probability that a CB state of energy E_2 is occupied by an electron and a VB state of energy E_1 is empty (occupied by a hole).

$$f_e(\nu) = f_c(E_2)[1 - f_v(E_1)]$$

Absorption probability that a CB state of energy E_2 is empty (occupied by a hole) and a VB state of energy E_1 is occupied by an electron.

$$f_a(\nu) = [1 - f_c(E_2)]f_v(E_1)$$

where $E_2 - E_1 = h\nu$

In thermal equilibrium: $f_e(\nu) < f_a(\nu)$

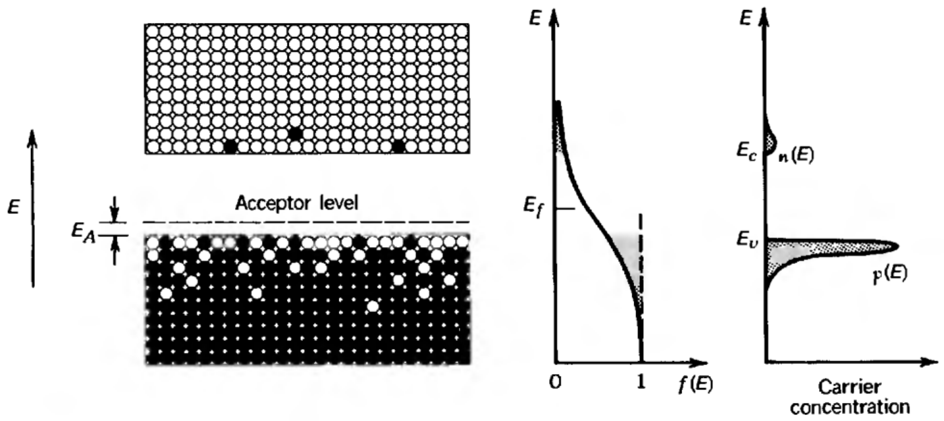
In quasi-equilibrium: emission is more probable than absorption if $f_e(\nu) > f_a(\nu)$. This occurs when the **quasi-Fermi levels are**

$$\boxed{E_{fc} - E_{fv} > h\nu}$$

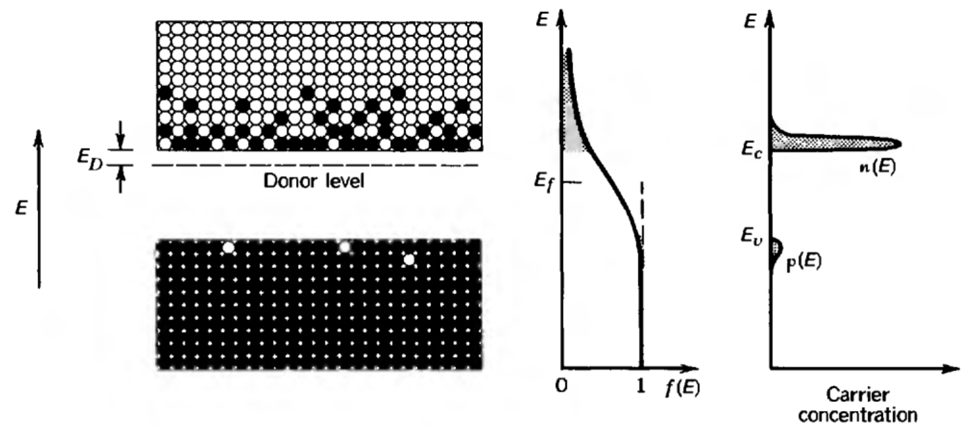
Condition for net emission

Doped semiconductors

p-type: Impurities with deficiency of valence electrons (acceptors)



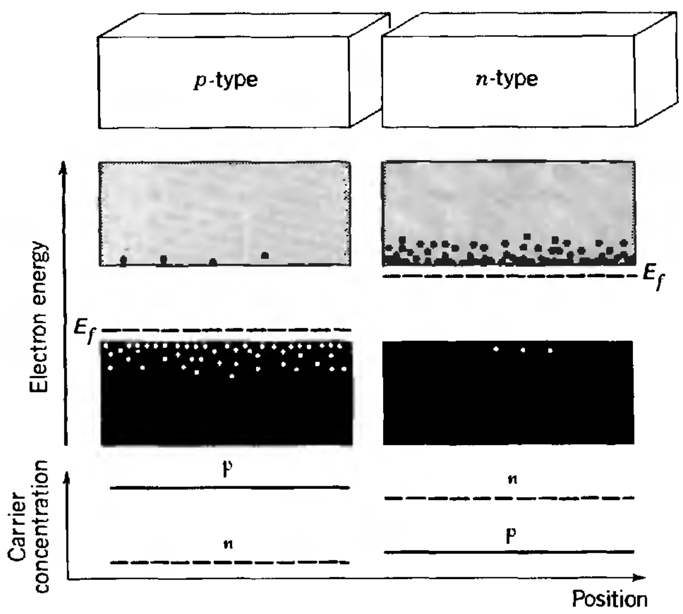
n-type: Impurities with excess of valence electrons



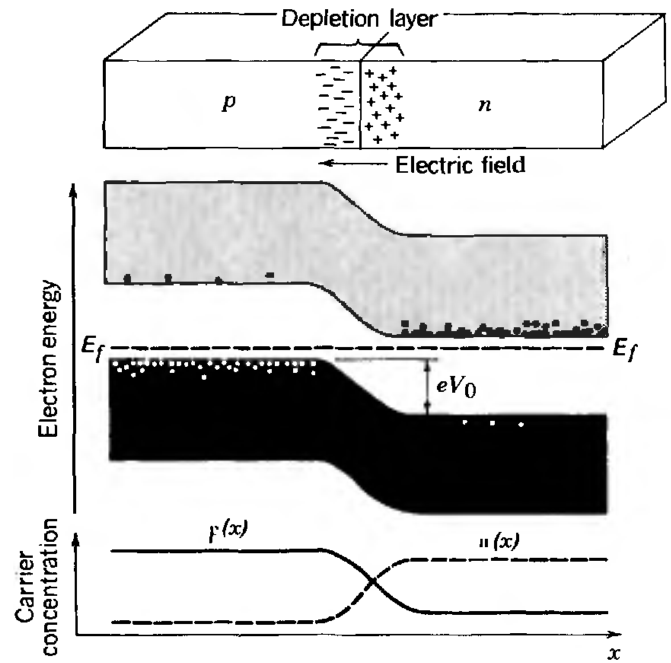
Group IV atoms act as donors in group III and as acceptors in group V

The p-n junction

Before contact



After contact

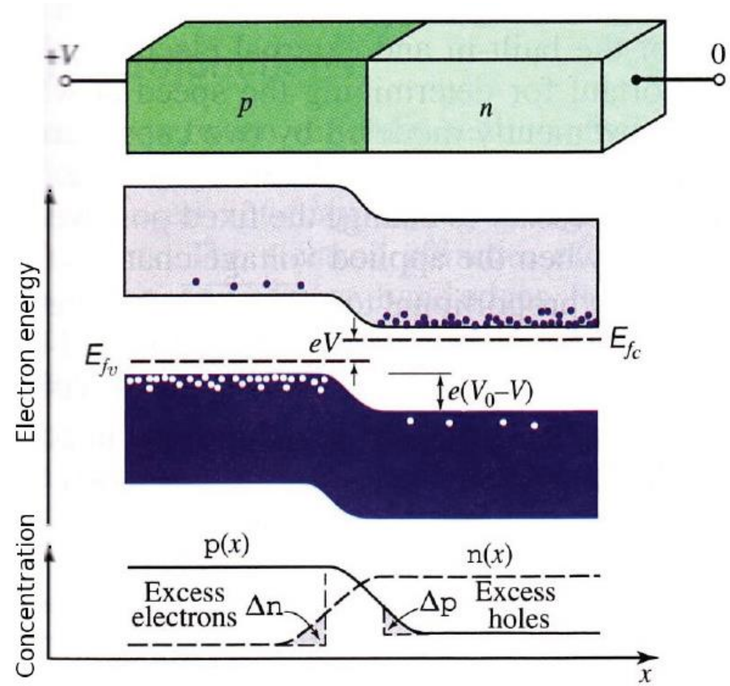


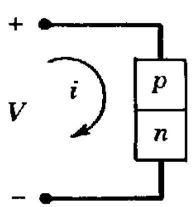
- Mobile electrons and holes **diffuse.**
- Leave behind a region ("**depletion layer**") that contains only fixed charges
- These fixed charges create an electric field that obstructs the diffusion of mobile charges.

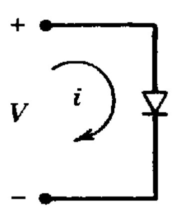
The biased p-n junction

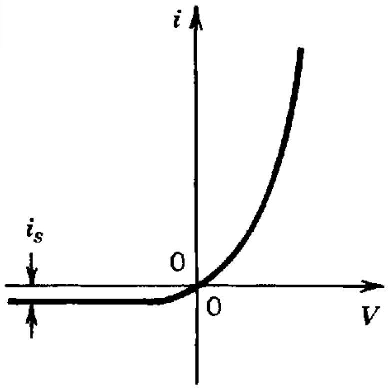
- By applying a positive voltage to the p-region, the electric field changes direction and current can flow across the junction.

⇒ The p-n junction acts as a diode





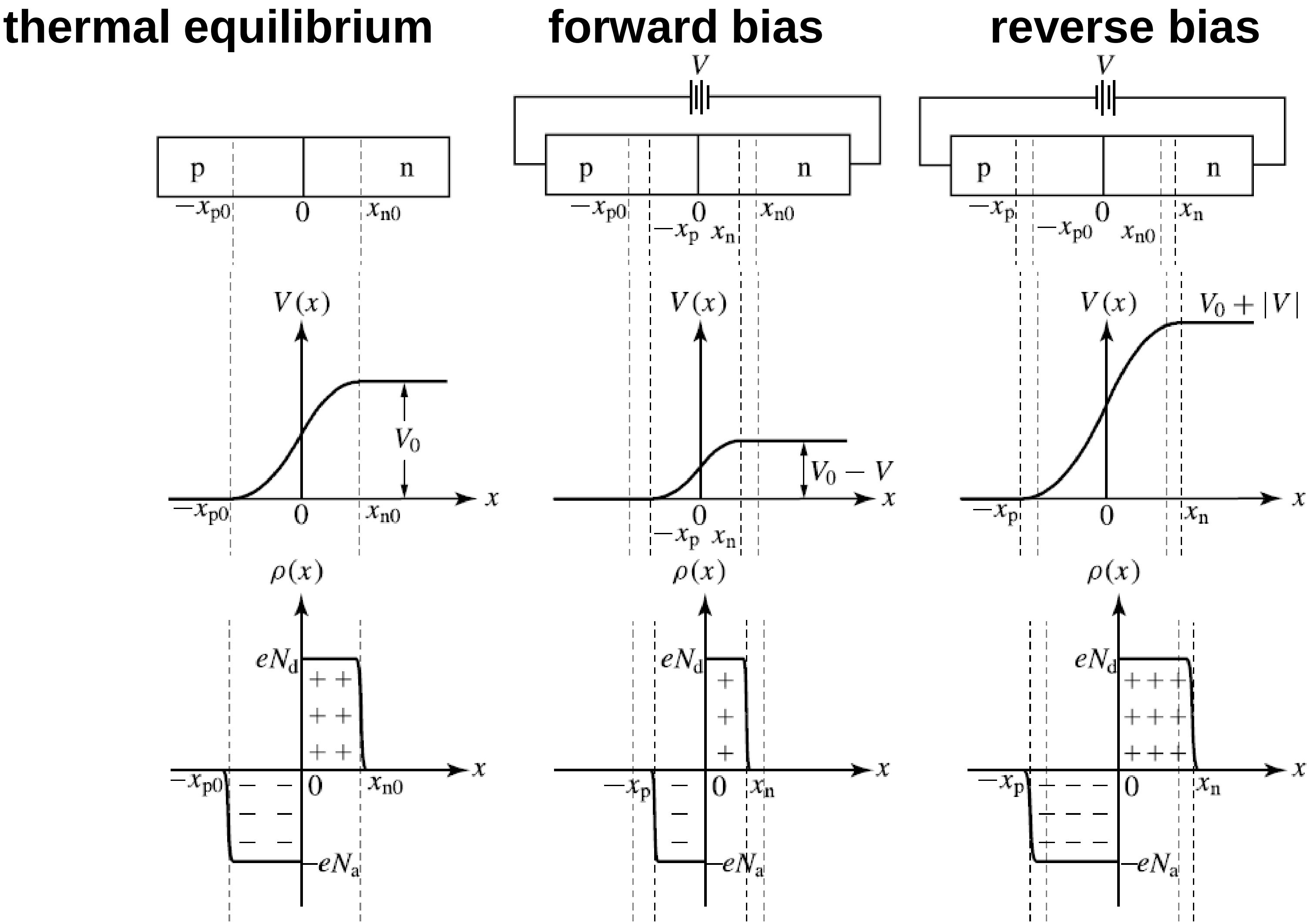




First semiconductor lasers were p-n junctions

(“Homo-structures”)

Depletion layer in a p–n homojunction



Summarizing

- Electron/hole diffusion generate a “depletion layer” at the p-n junction (the carrier diffusion length is an important parameter of semiconductor materials).
- With forward bias electron/hole recombination at junction: converts electrical current into light.
- Concentrating “carriers” and photons at the junction is crucial for efficiency.
- Next: brief overview of the interactions of photons with electrons and holes in a semiconductor material.

Outline

- Introduction
- Semiconductor materials
- **Photons in semiconductors**
- Semiconductor light sources
  - LEDs
  - Amplifiers
  - Semiconductor lasers

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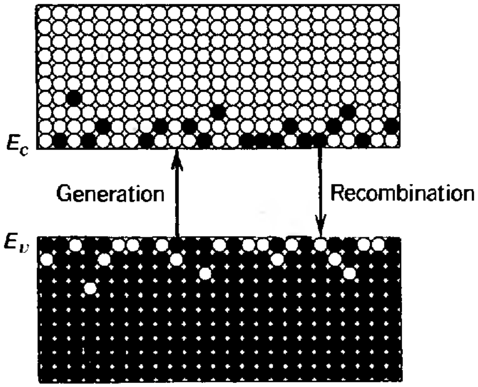
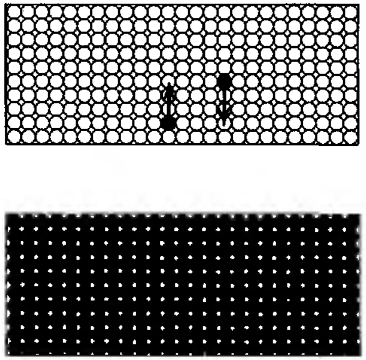
Bibliography: *Fundamentals of Photonics*, B.E.A. Saleh and M.C. Teich
Photonic devices, J. M. Liu

Photon/carrier interactions

- Inter-band (Band-to-band):
  - absorption
  - stimulated emission
  - spontaneous emission
- Intra-band (Quantum cascade lasers)
- Others:
  - Impurity-to-band (Shockley–Read)
  - Excitonic (exciton: e/h pair held together by their Coulomb attraction –like a hydrogen atom but with a hole instead of a proton. More latter about exciton-polariton lasers)
  - Auger (electron-hole + third carrier)
  - Phonon (long wavelength photons excite directly lattice vibrations -phonons)

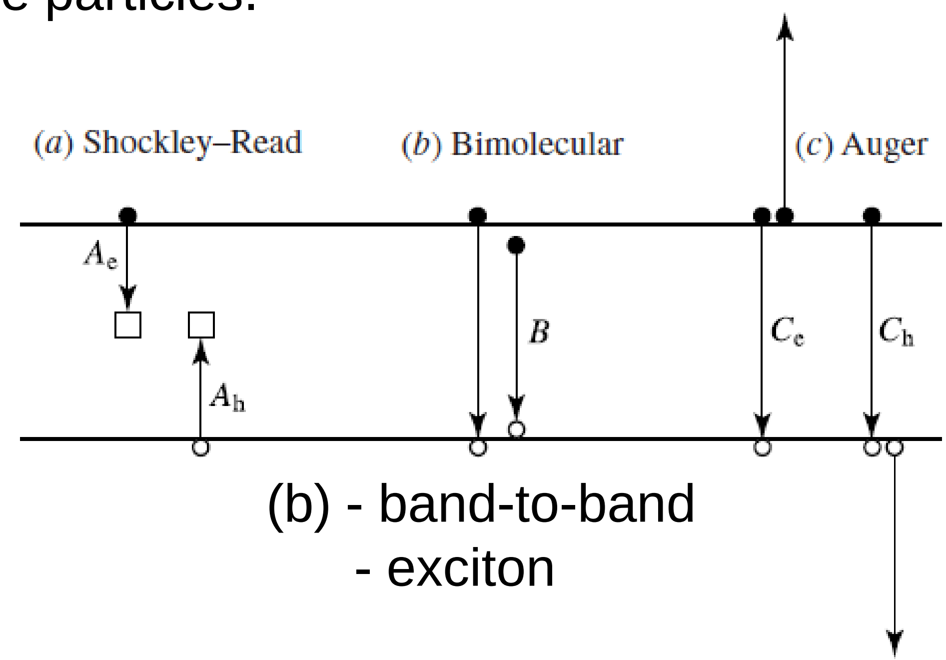




Carrier recombination processes

- Shockley–Read (SR) recombination: one carrier at a time.
- Bimolecular recombination: e/h simultaneously.
- Auger: three particles.

(a) Carrier capture by an impurity.
It can be radiative or nonradiative depending on the type of impurity



(b) - band-to-band
- exciton

(c) the energy released by band-to-band recombination of an e/h pair is picked up by a third carrier.

- A photon emitted by band-to-band recombination has an energy slightly higher than the bandgap.
- A photon emitted through a process involving the impurities (SR recombination) has an energy lower than the bandgap.

Shockley–Read radiative recombination through impurity states

- Is important in indirect-gap semiconductors, in which band-to-band radiative recombination probabilities are very low.
- In particular, this process is responsible for improving the luminescence efficiency of the indirect-gap semiconductors for their applications as materials for LEDs.
- For example, N and ZnO impurities in GaP act as electron traps.

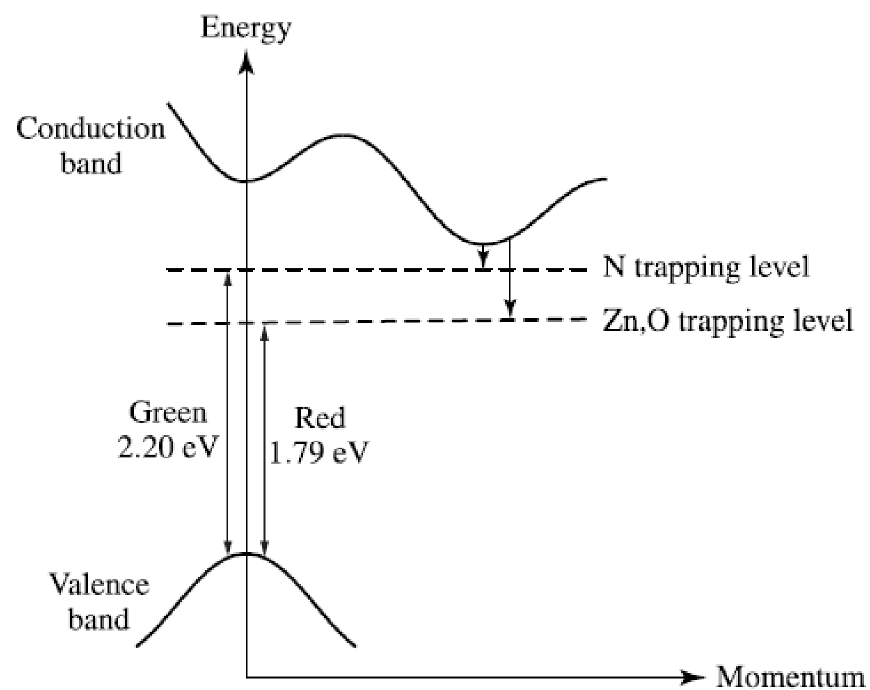


Figure 13.1 Isoelectronic trapping levels of N and Zn,O centers in GaP.

Carrier recombination rate

$$R = AN + BN^2 + CN^3$$

A: Shockley–Read coefficient

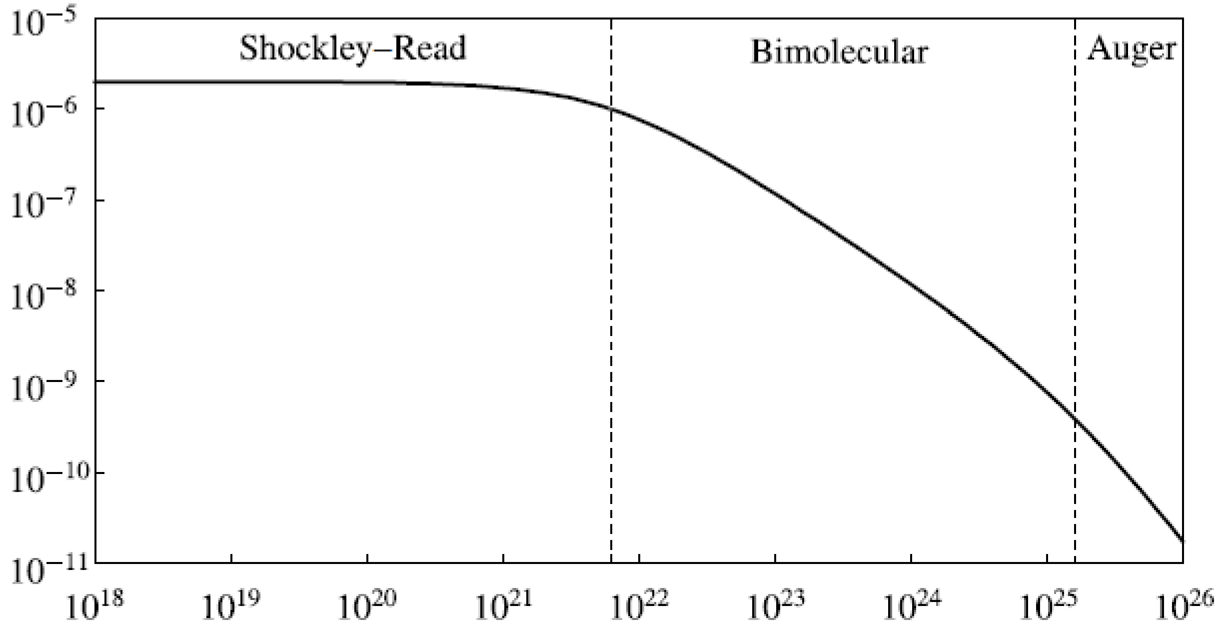
B: bimolecular recombination coef.

C: Auger recombination coef.

- Only Shockley–Read is important at low carrier concentration.
- The Auger process can be significant only at very high carrier concentration.
- Between the two limits, the bimolecular recombination process can be the dominant recombination process.
- B coefficient is orders of magnitude larger in direct-gap (GaAs, InP) than in indirect-gap (Si, Ge) semiconductors.

Carrier lifetime: $\tau_N = \dfrac{N}{R}$

$\tau_N\,(\mathrm{s})$



$N\,(\mathrm{m}^{-3})$

$$\frac{1}{\tau_N} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

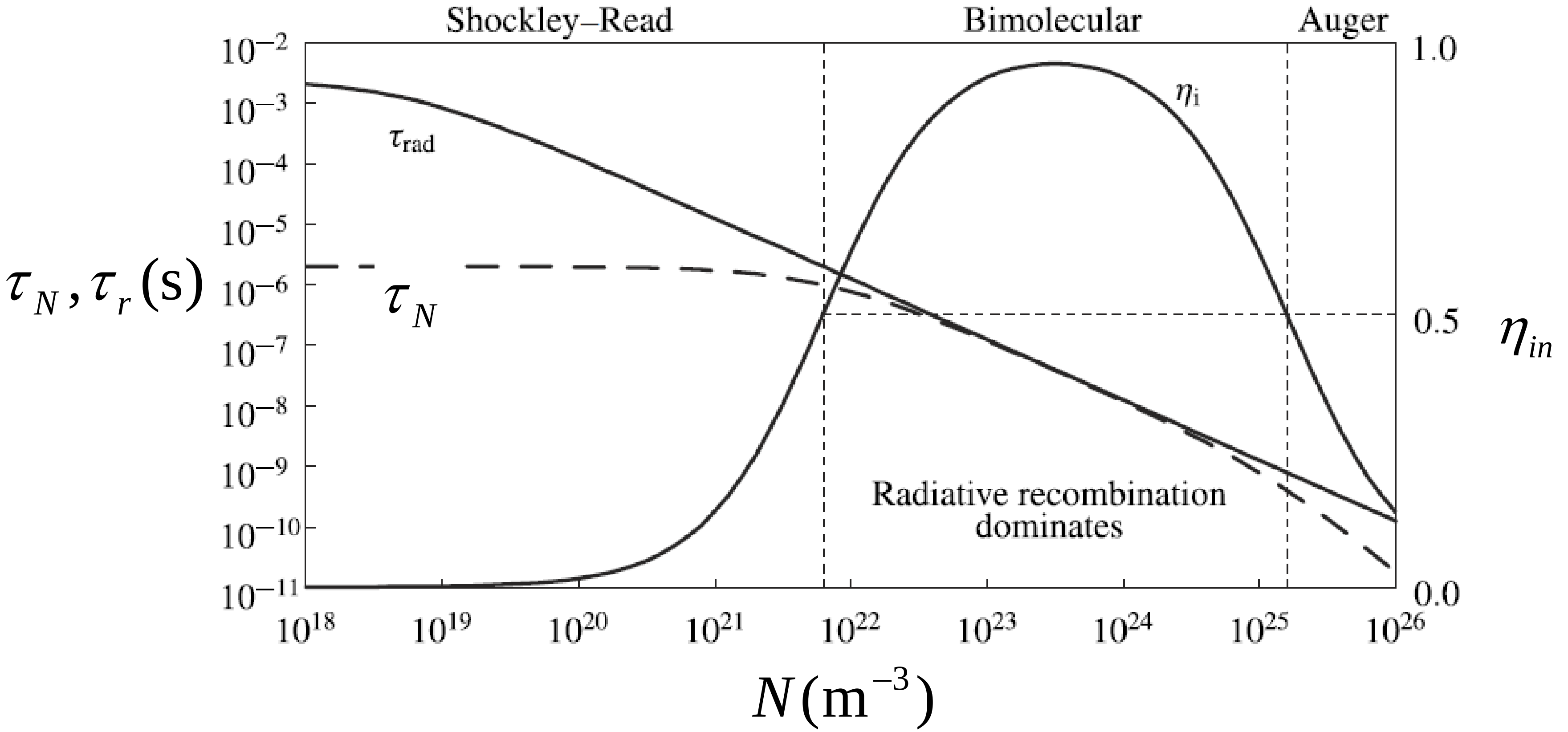
τ_r: radiative lifetime

τ_{nr}: non-radiative lifetime

Internal quantum efficiency

Fraction of the injected electron flux that is converted into photon flux: radiative / total recombination rate

$$\eta_{in} = \frac{1/\tau_r}{1/\tau_N}$$



Rates of spontaneous emission, stimulated emission and absorption

$$r_{sp}(\nu) = \frac{1}{\tau_r}\varrho(\nu) f_e(\nu)$$

$$r_{st}(\nu) = \phi_\nu \frac{\lambda^2}{8\pi\tau_r}\varrho(\nu) f_e(\nu)$$

$$r_{ab}(\nu) = \phi_\nu \frac{\lambda^2}{8\pi\tau_r}\varrho(\nu) f_a(\nu)$$

r_{sp}, r_{st} & r_{ab} : [m^{-3}]

ϕ_ν: Photon flux = number of photons per second per unit area and per Hz) [m^{-2}]

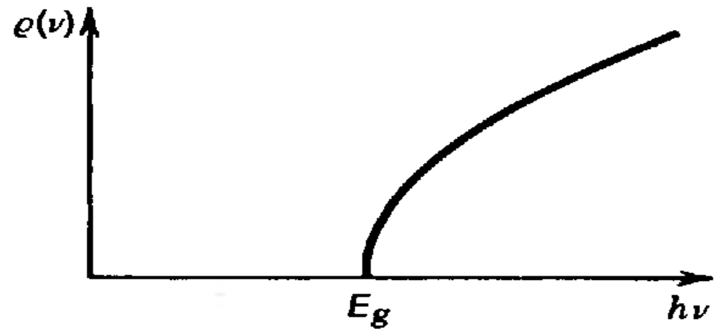
τ_r: radiative lifetime [s]

$\varrho(\nu)$: Density of states [m^{-3} Hz^{-1}]

Occupancy probabilities

$$f_e(\nu) = f_c(E_2)[1 - f_v(E_1)]$$

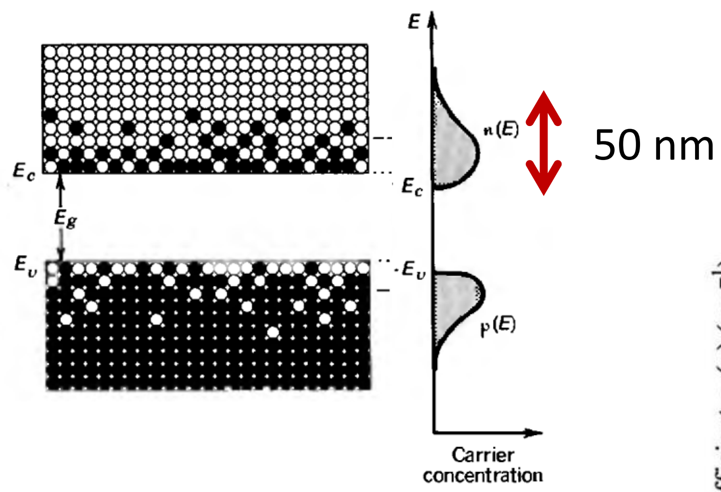
$$f_a(\nu) = [1 - f_c(E_2)] f_v(E_1)$$



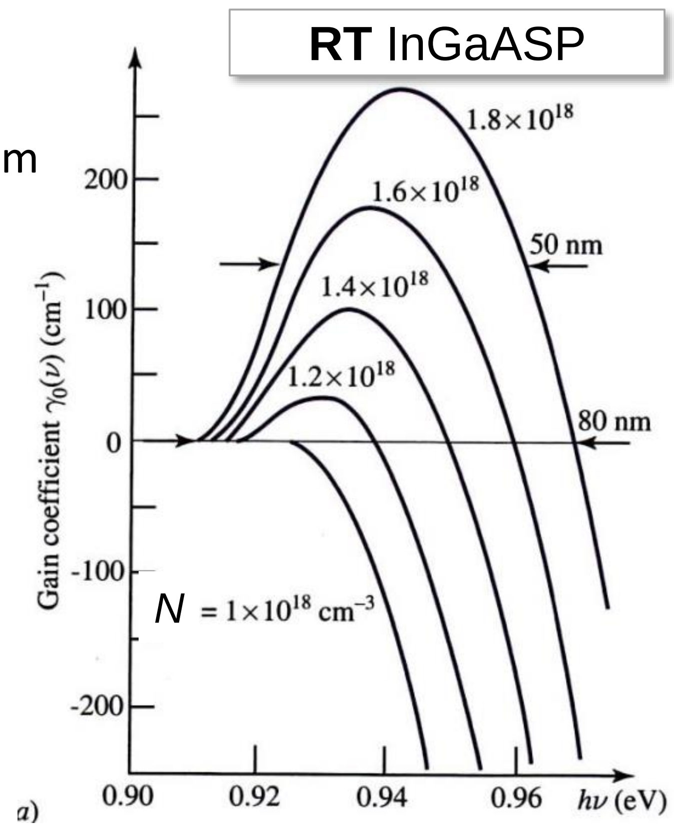
Semiconductor gain G(N,ν,T)

Gain coef. = (rate of stimulated emission – absorption) / incident photon flux

$$\gamma_0(\nu) = [r_{st}(\nu) - r_{ab}(\nu)]/\phi_\nu \quad [\mathrm{cm}^{-1}]$$



Gain bandwidth depends of the carrier density, *N*, and of the temperature, *T*.

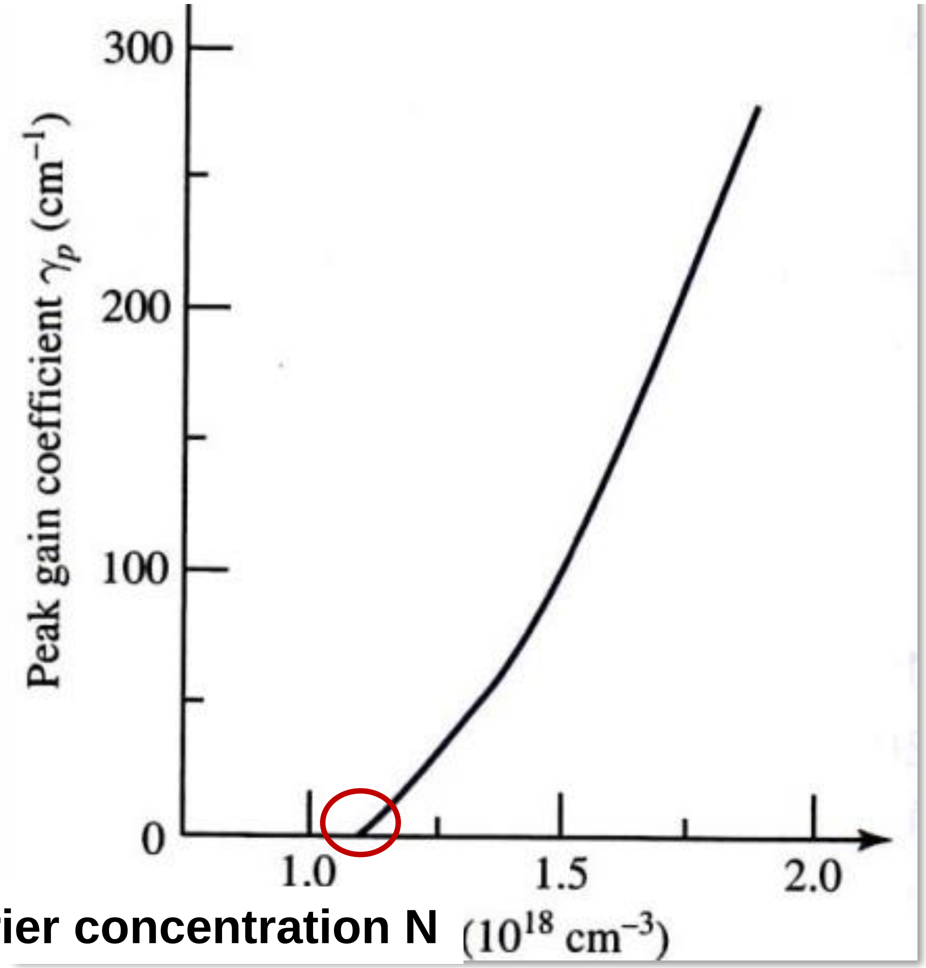


The semiconductor gain spectrum is asymmetric.

The gain bandwidth and the peak value of the gain coefficient increase with the carrier density *N*.

Transparency condition

The semiconductor material becomes "transparent" when the rate of absorption is equal to the rate of stimulated emission.



- At transparency one incident photon produces one photon in the output.

- The *transparency density* is the excess density of electrons in the conduction band required to achieve transparency.

Linear approximation

$$\boxed{\gamma_p = a\,(N - N_0)}$$

N_0: transparency carrier density
a: differential gain [cm^2]

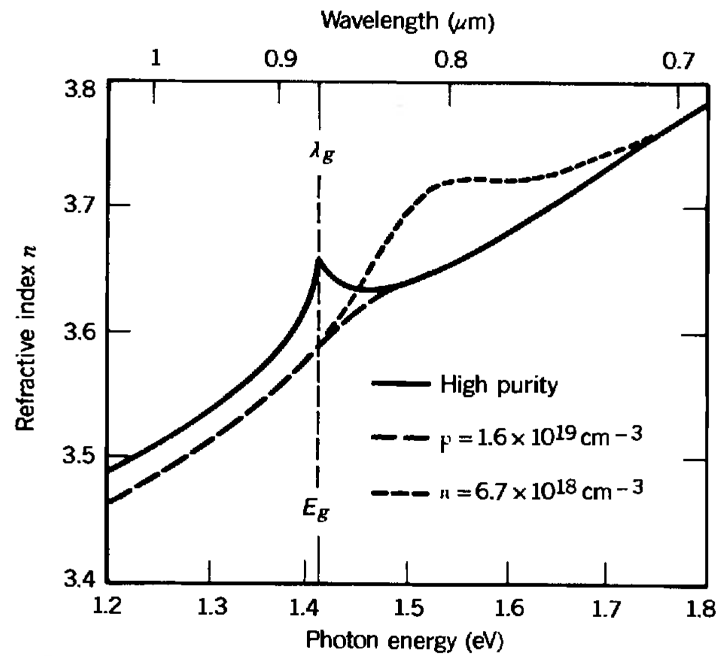
Refractive index n(N,ν,T)

- Is related to gain by the Kramers-Kroning relations
  [gain ~ − Im(χ), n ~ Re(χ)] ⇒ n also depends on N, λ, T.

At T=300 K

Material	Refractive Index
Elemental semiconductors	
Ge	4.0
Si	3.5
III–V binary semiconductors	
AlP	3.0
AlAs	3.2
AlSb	3.8
GaP	3.3
GaAs	3.6
GaSb	4.0
InP	3.5
InAs	3.8
InSb	4.2

GaAs at T=300 K

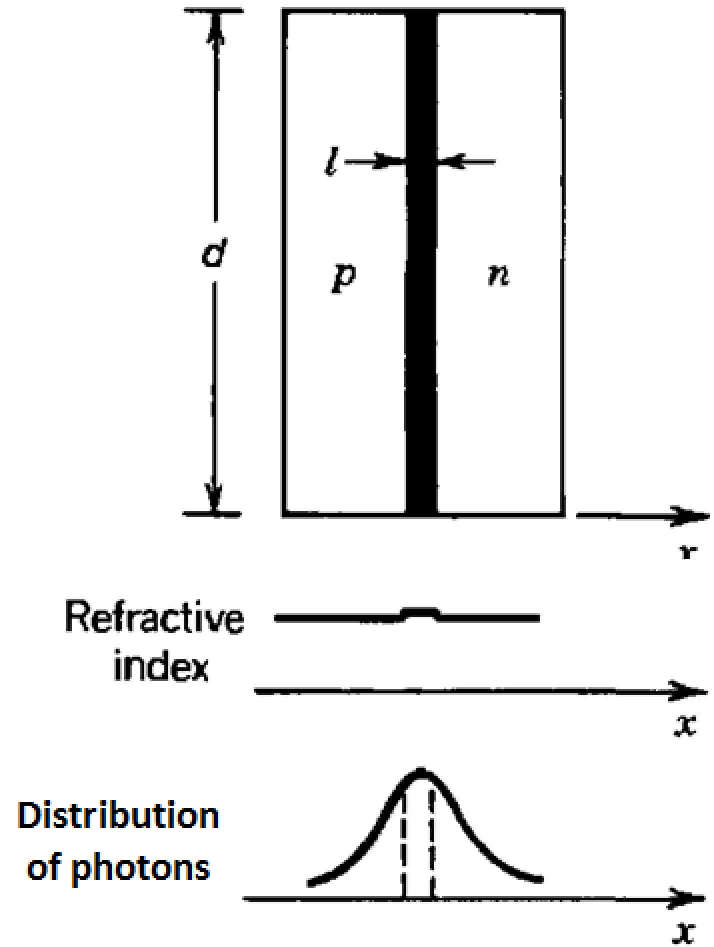


The peak in the high-purity curve is associated to free excitons.

Carrier-induced waveguide

The first generation of diode lasers were "homo-junctions"

The electron/hole concentration in the depletion layer modifies the refracting index, creating a **wave guide** that helps to confine the photons



Thermal effects

- Temperature affects the **gain** (the peak and the width).
- This causes a variation of the **refractive index** [via the Kramers-Kronig relations: gain ~ ─ Im(χ), n ~ Re(χ)].

GaAs

$$E_g = 1.5216 - \frac{5.405 \times 10^{-4}\, T^2}{T + 204}\ \text{(eV)}$$

InP

$$E_g = 1.4206 - \frac{4.906 \times 10^{-4}\, T^2}{T + 327}$$

At 300 K:

$$\frac{1}{n}\frac{\mathrm{d}n}{\mathrm{d}T} = 4.5 \times 10^{-5}\ \mathrm{K}^{-1}$$

$$\frac{1}{n}\frac{\mathrm{d}n}{\mathrm{d}T} = 2.7 \times 10^{-5}\ \mathrm{K}^{-1}$$

TF test

- Si and Ge are important materials for photo-detectors but are not useful as light sources.
- The composition of ternary compounds can be varied to adjust both, the lattice constant and the band-gap.
- The composition of quaternary compounds can be varied to adjust both, the lattice constant and the band-gap.
- The electron/hole occupancy probabilities in the conduction/valence bands are independent of the temperature.
- The length of the “depletion layer” depends on the diffusion length of electrons and holes.
- In a semiconductor the refractive index is independent of the carrier concentration.
- The “depletion layer” acts as a waveguide for confining the photons.

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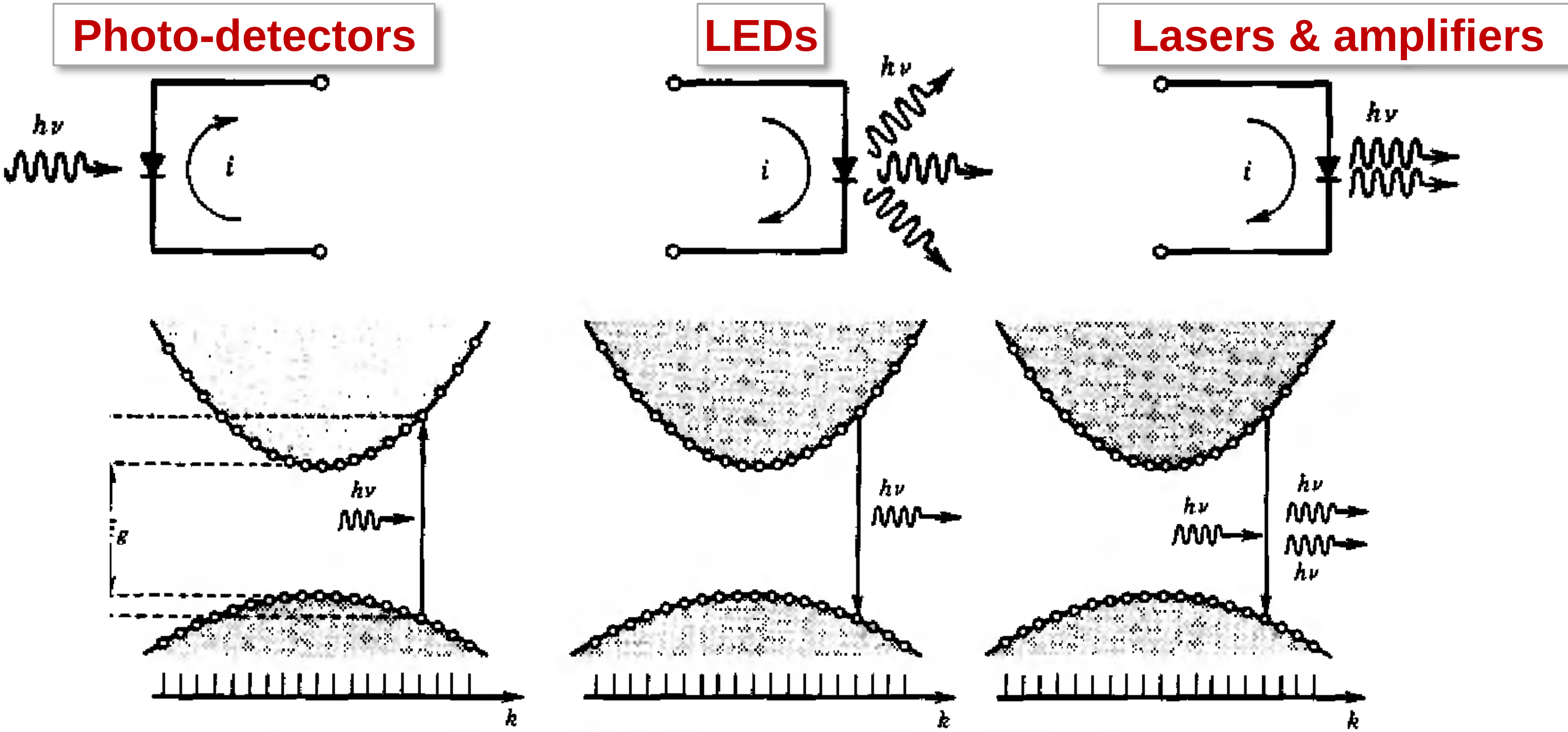
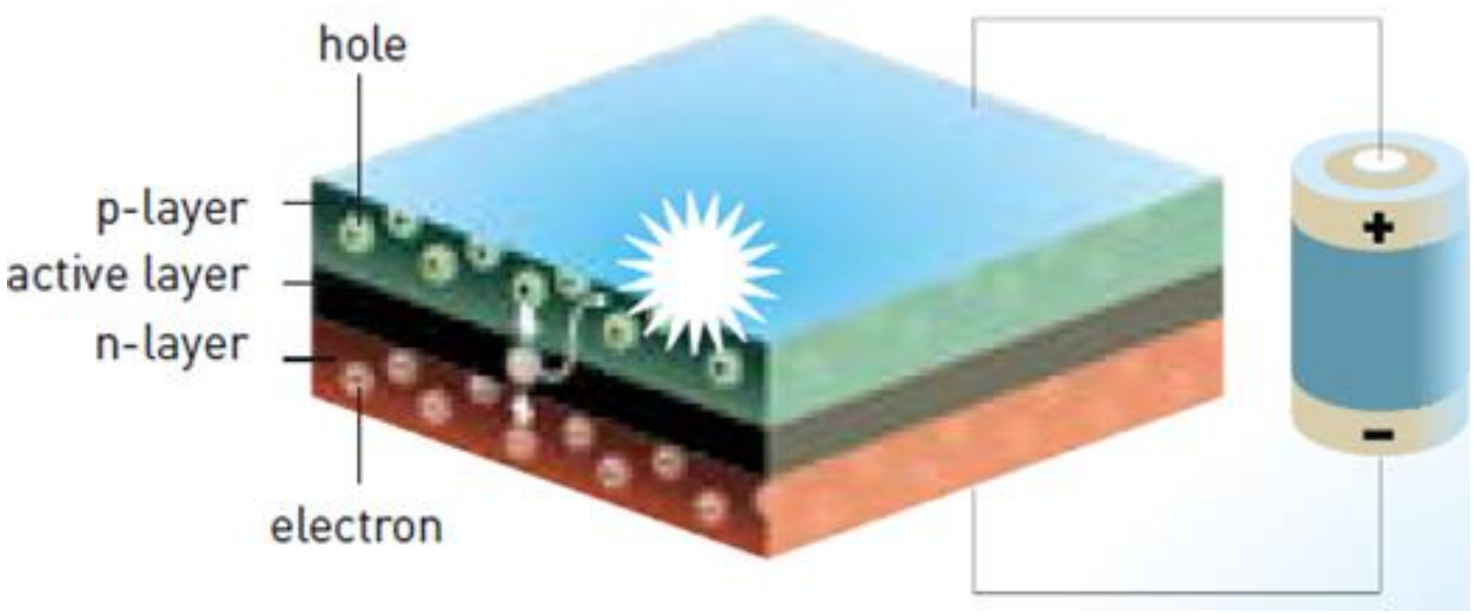
Bibliography: *Fundamentals of Photonics*, B.E.A. Saleh and M.C. Teich

Band-to-band transitions: absorption, spontaneous and stimulated recombination



LEDs operation principle: spontaneous recombination

Electro-luminescence (inverse of the photo-electric effect)



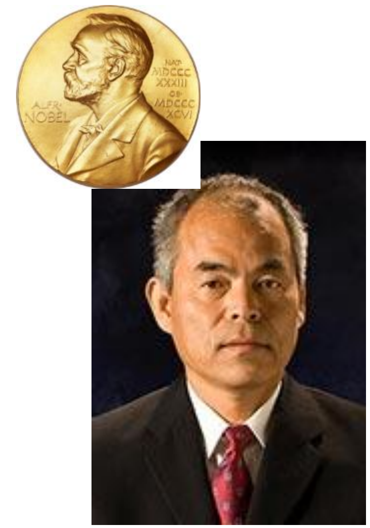
- The light's wavelength depends on the material used.
- LED's size < a grain of sand.

Green, **yellow** and **red** versions were invented in the 1950s and were used in calculator displays, "on/off" light indicators, etc.

The 2014 Nobel Prize in Physics

Isamu Akasaki
Nagoya University
Japan

Hiroshi Amano
Nagoya University
Japan

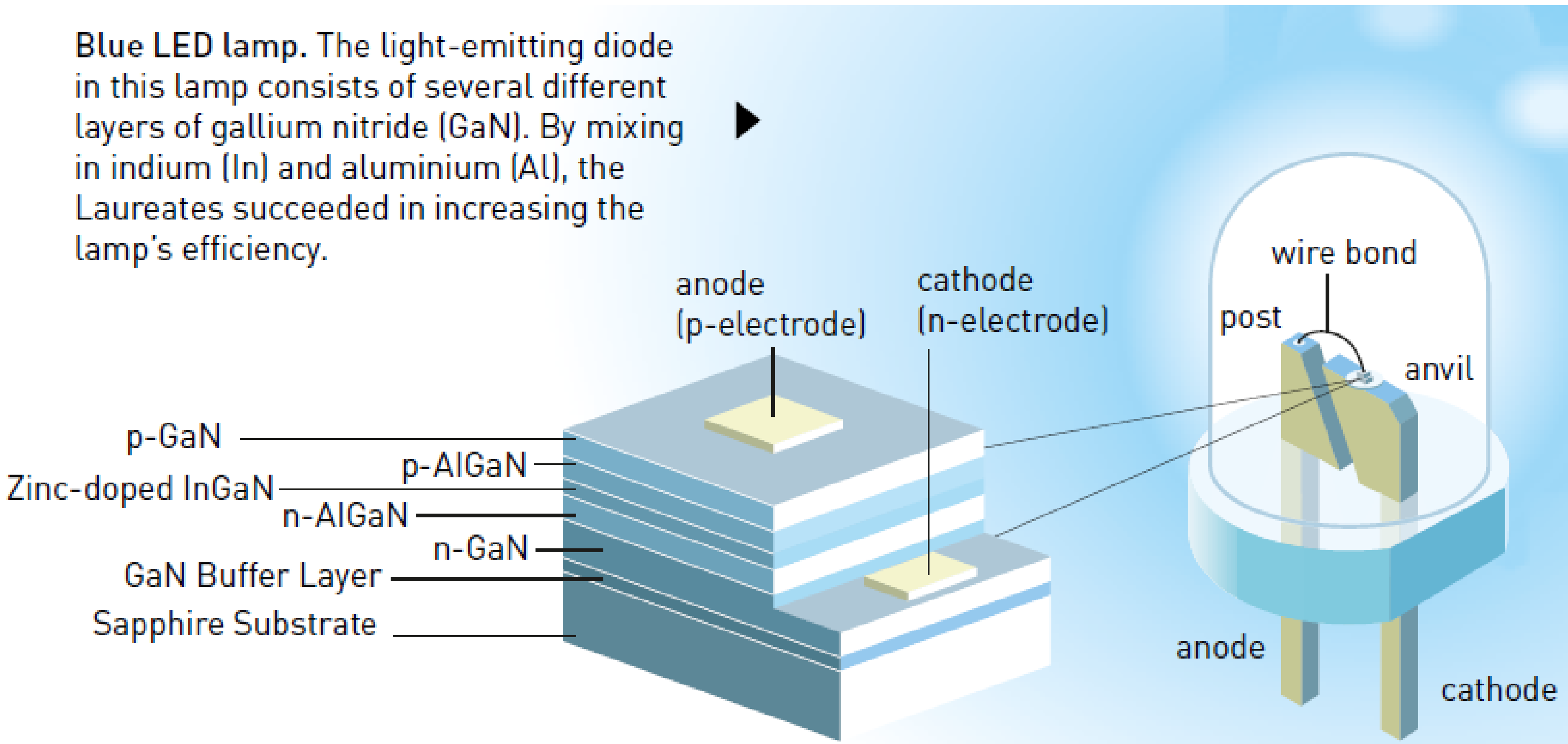


Shuji Nakamura
University of California
Santa Barbara, US

*"for the invention of efficient **blue** LEDs which has enabled bright and energy-saving white light sources"*

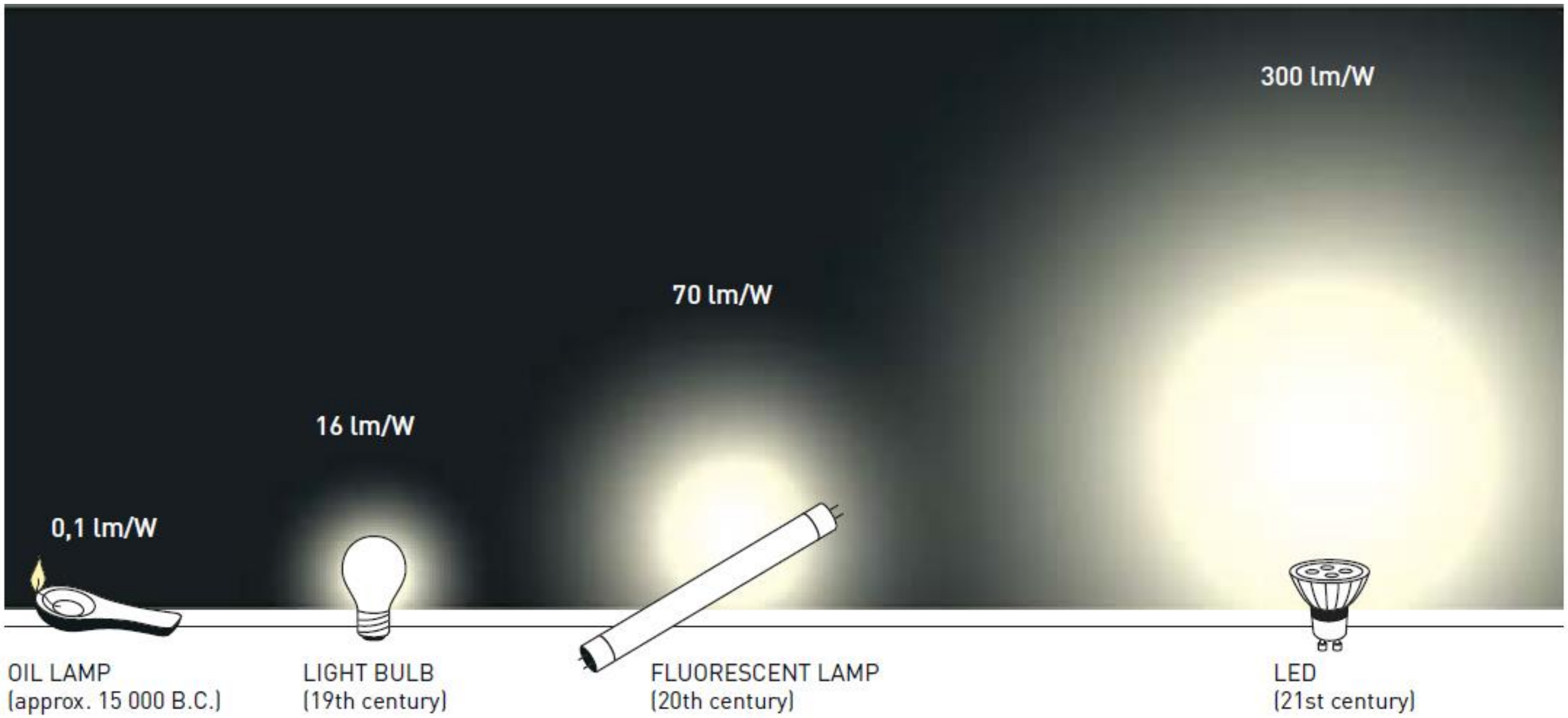
Blue LED: how does it work?

Based on gallium nitride (GaN), blue LEDs are combined with fluorescent materials to realize white light.



Why the Nobel Price?

LED lamps are very efficient!



- About ¼ of world electricity consumption is used for lighting.
- The highly energy-efficient LED lamps contribute to saving up to 20% of the global electricity consumption.

The life and times of the LED — a 100-year history

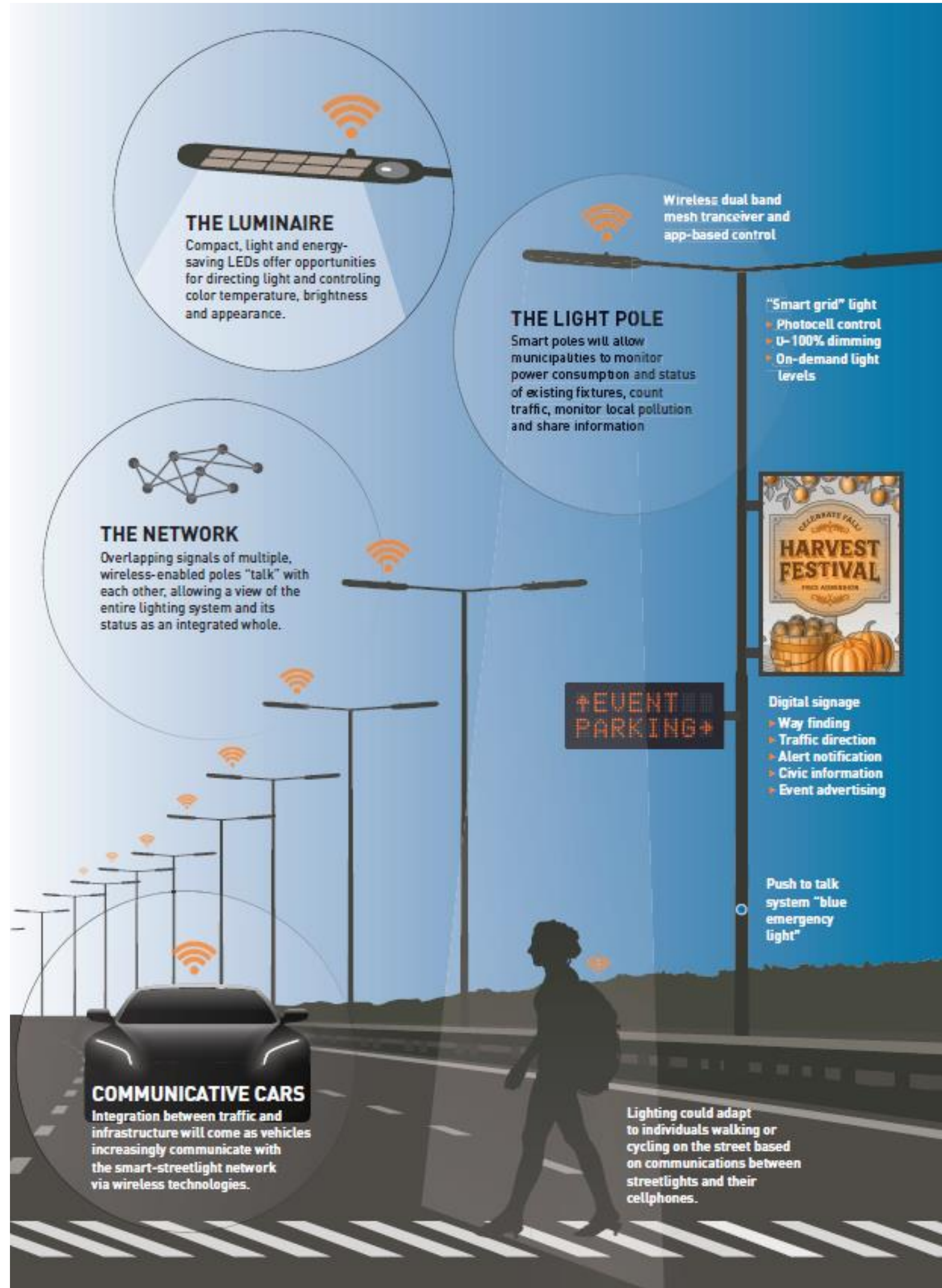
NIKOLAY ZHELUDEV

is at The Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK.
e-mail: n.i.zheludev@soton.ac.uk

Many people believe that the LED was dicovered by US researchers working in the 1960s. In fact, Henry Round at Marconi Labs noted the emission of light from a semiconductor diode 100 years ago and, independently, a forgotten Russian genius — Oleg Losev — discovered the LED.

Source: Nature Photonics April 2007

How LEDs Are Enabling “Smart Cities”

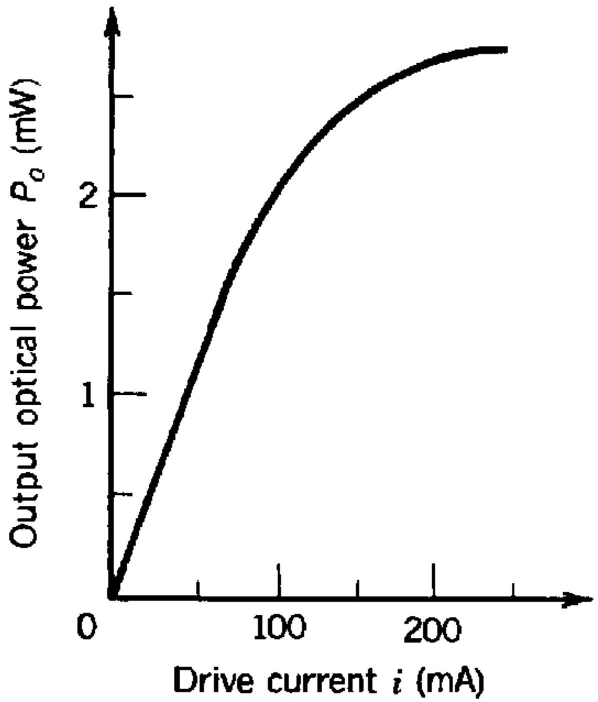


Source: Optics and Photonics News November 2018

LED: LI curve and efficiency

- Optical power: $P = h\nu\, \Phi$ (in Watts)

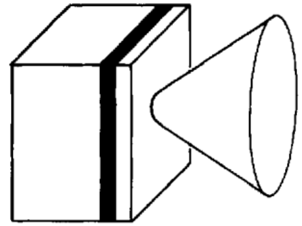
  where Φ is the flux of emitted photons (number of photons per unit time).
- $\Phi = \eta_{ex}\, I/e$ (I in Amperes)
- η_{ex} is the **external quantum efficiency**: accounts for the fact that
  - only a fraction of the injected electron flux (I/e=electrons per second) is converted into photon flux (**internal quantum efficiency**)
  - only a fraction of the generated photons emerge from the device.
- $P = h\nu\, \eta_{ex}\, I/e = 1.24\, \eta_{ex}\, I/\lambda$ (λ in μm)



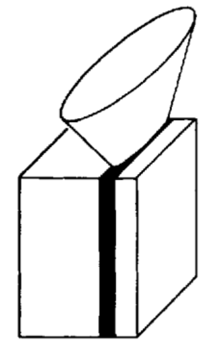
- Another measure: Responsivity = P/I

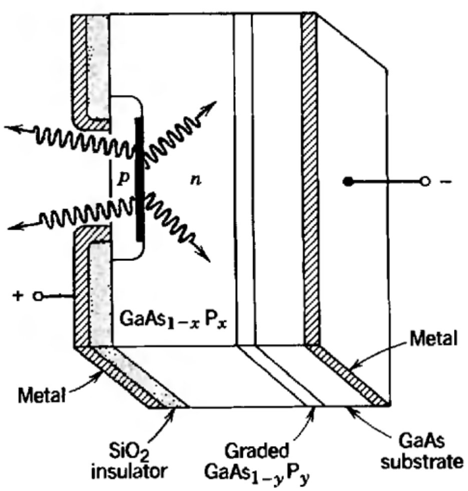
LED: structures

Surface-emitting

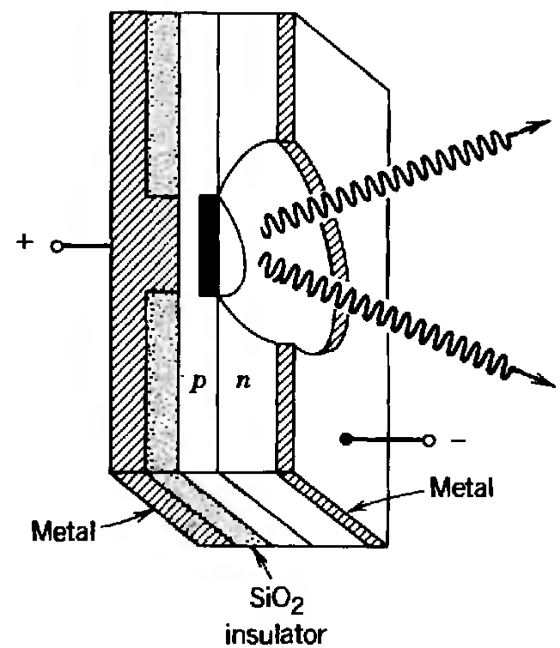


Edge-emitting





Light emitted from the opposite face is either absorbed or reflected.



Burrus-type LED: light is collected directly from the active region (efficient coupling into an optical fiber).

LED: optical spectrum

Rate of spontaneous emission:

$$r_{sp}(\nu) = D(h\nu - E_g)^{1/2} \exp\left(-\frac{h\nu - E_g}{k_B T}\right), \qquad h\nu \geq E_g$$

$$D = \frac{(2m_r)^{3/2}}{\pi \hbar^2 \tau_r} \exp\left(\frac{E_{fc} - E_{fv} - E_g}{k_B T}\right)$$

Peak frequency

$$h\nu_p = E_g + \frac{k_B T}{2}$$

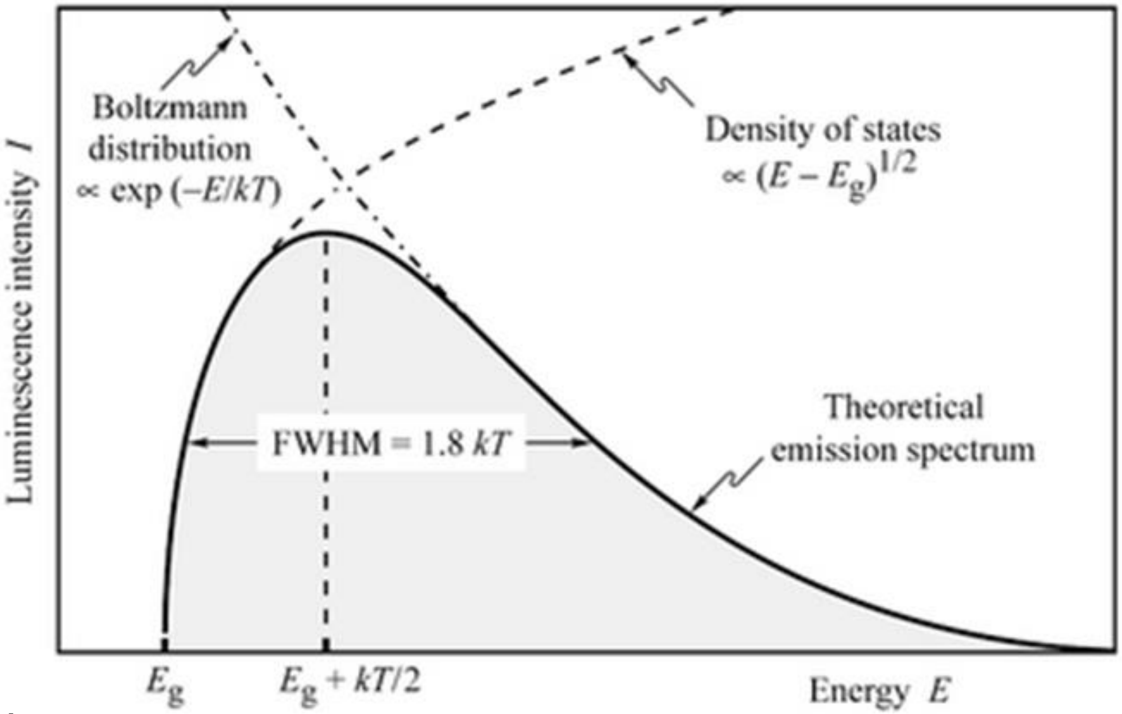
FWHM

$$\Delta\nu \approx \frac{1.8 k_B T}{h}$$

(10 THz when T = 300 K)

$$\Delta\lambda \approx 1.45 \lambda_p^2 k_B T$$

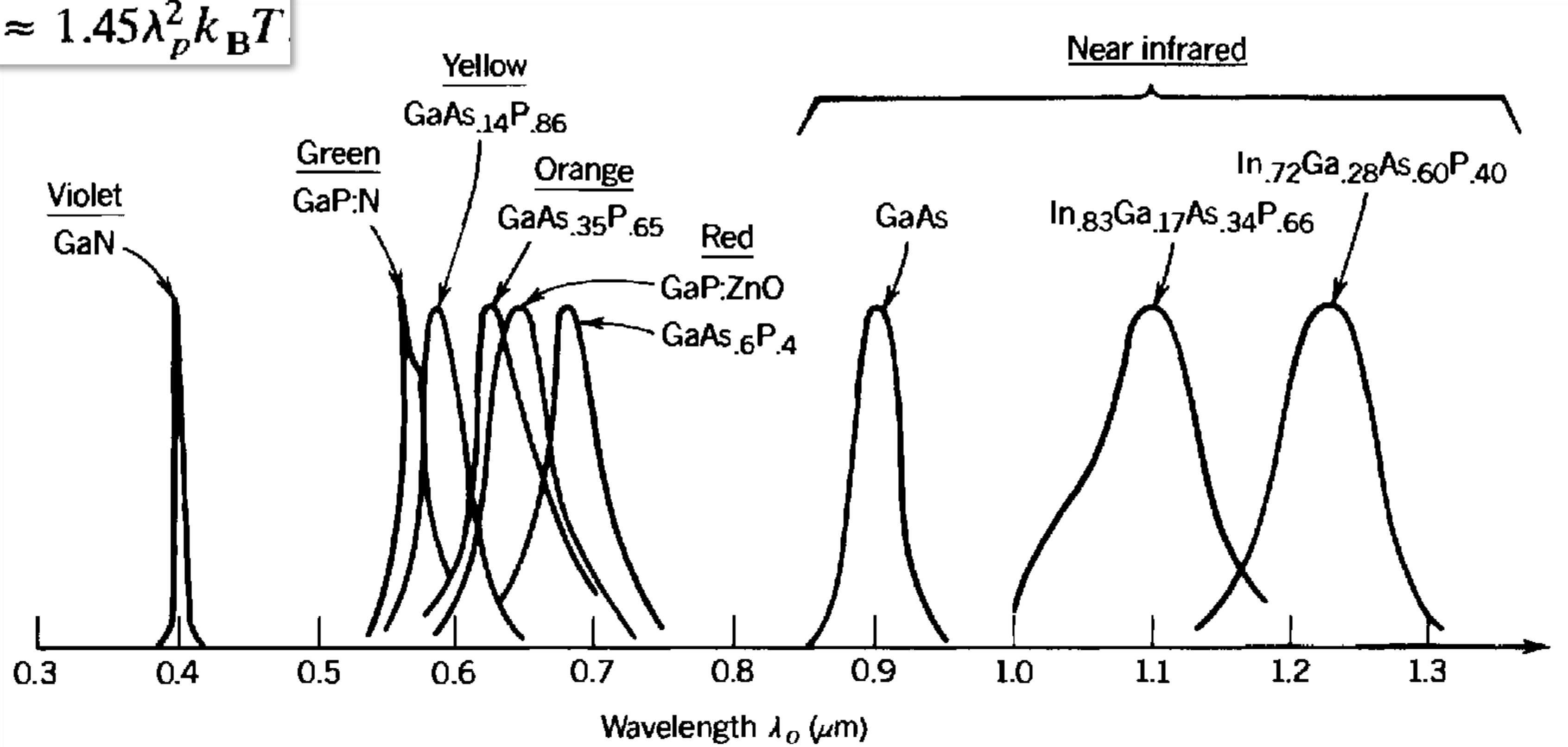
(when $k_B T$ in eV and λ_p in μm)



λ_p = 1 μm at T= 300 K: $\Delta\lambda$ = 36 nm

LED linewidth vs. wavelength

$$\Delta\lambda \approx 1.45\lambda_p^2 k_B T$$



Outline

- Introduction
- Semiconductor materials
- Photons in semiconductors
- Semiconductor light sources
  - LEDs
  - **Amplifiers**
  - Semiconductor lasers

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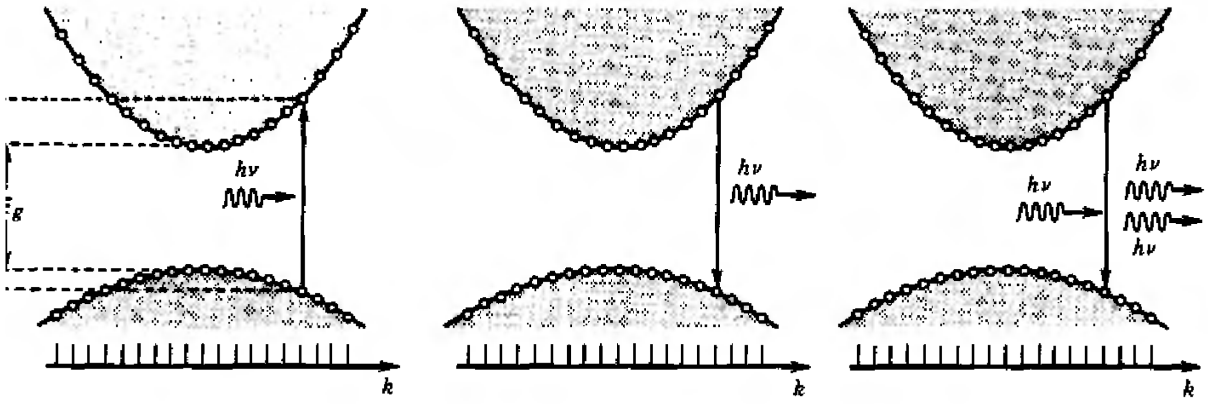
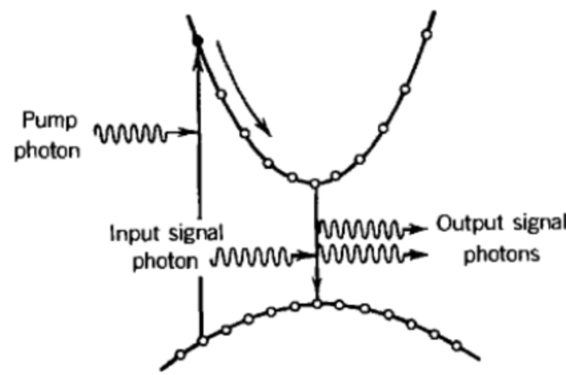
Bibliography: *Fundamentals of Photonics*, B.E.A. Saleh and M.C. Teich

How do amplifiers work?

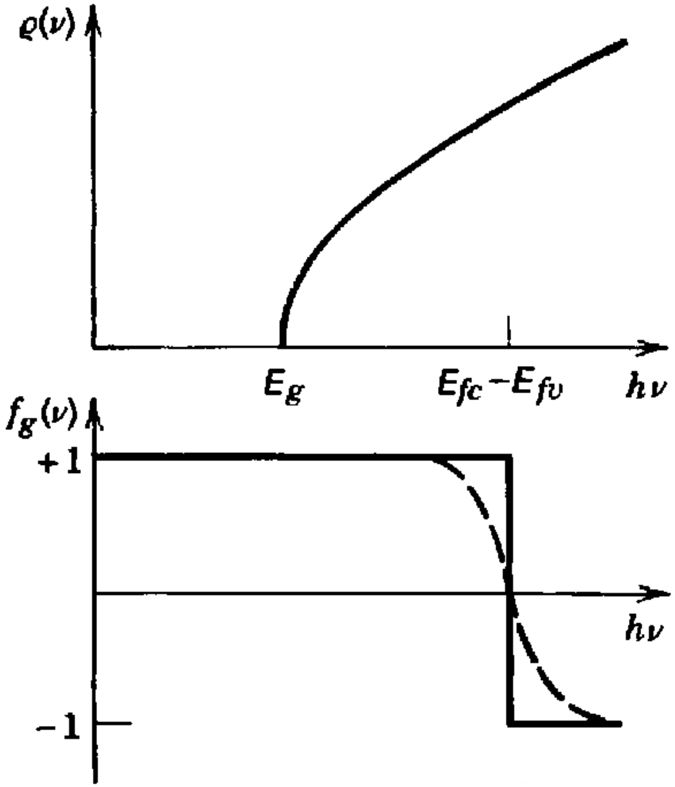


- Operation principle: stimulated emission.
- e/h concentrations have to be large enough to overcome absorption:
  – <u>Optically pumped</u>: e/h generated by high energy photons ($>E_g$).
  – <u>Electrically pumped</u>: same as LEDs.



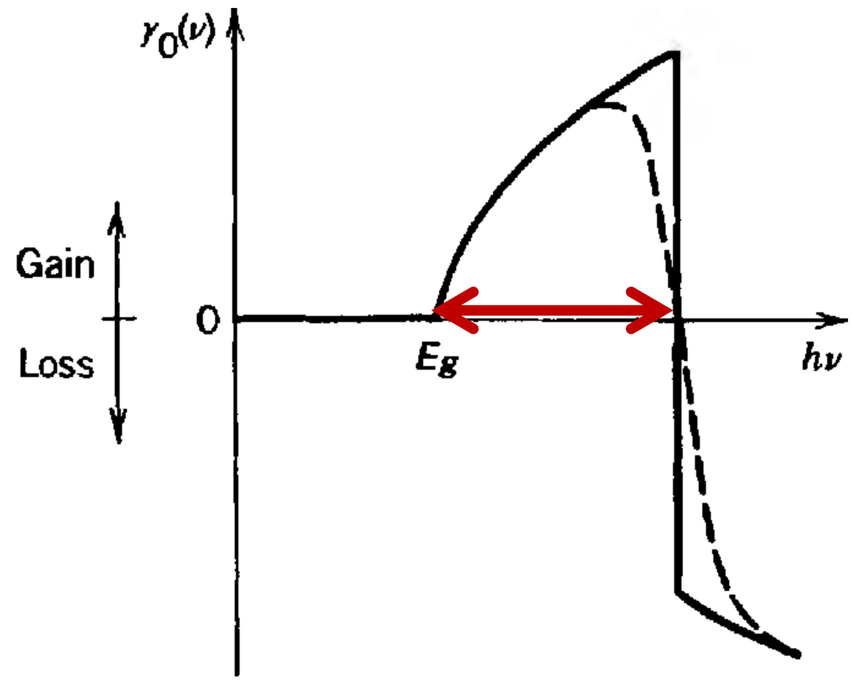
Amplifier bandwidth

Density of states



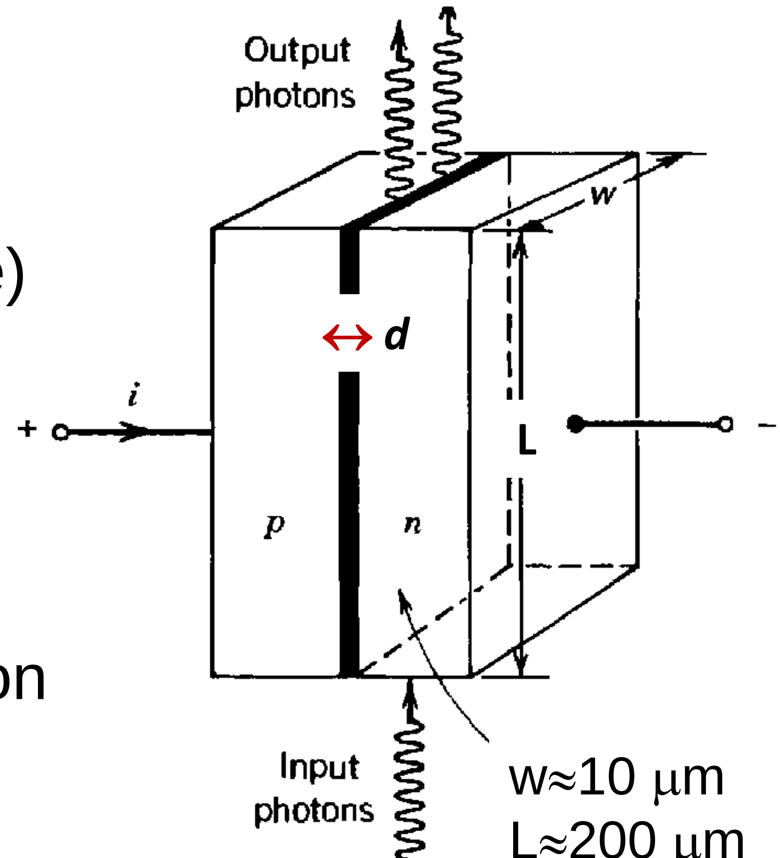
Fermi inversion factor
(solid T=0, dash RT)

Gain coefficient
(solid T=0, dash RT)



$$\gamma_0(\nu) = [r_{st}(\nu) - r_{ab}(\nu)]/\phi_\nu$$

Injected current density



w≈10 μm
L≈200 μm
d ≈0.1-2μm

$J = i / (w L)$ (Ampere per unit area)

$R = (i/e)/(w L d)$ (injection rate per second and per unit volume)

Steady-state injection condition:

Recombination rate x carrier concentration = injection rate

$$1/\tau_N \quad x \quad N \quad = \quad (i/e)/(w\,d\,L)$$

internal quantum efficiency: fraction of the injected electron flux that is converted into photon flux

$$\eta_{in} = (1/\tau_r) / (1/\tau_N) \Rightarrow 1/\tau_N = 1/(\eta_{in}\,\tau_r)$$

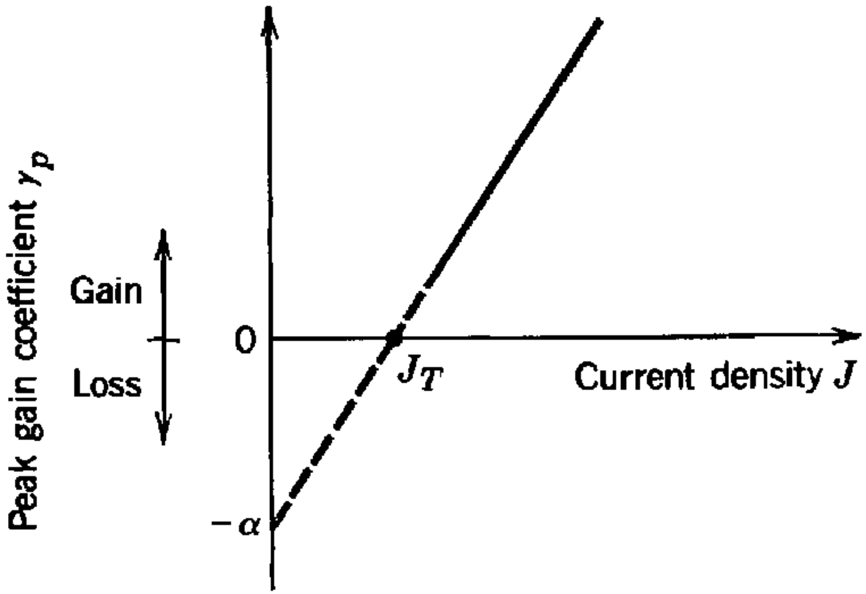
$$1/(\eta_{in}\,\tau_r)\,N = (i/e)/(w\,d\,L) = J/(ed) \Rightarrow \boxed{J = e\,d\,N / (\eta_{in}\,\tau_r)}$$

Amplifier gain and material transparency

Linear approximation of the peak gain coefficient:

$$\gamma_p = \alpha\,(J/J_T - 1)$$

$$\boxed{J_T = e\,d\,N_T / (\eta_{in}\,\tau_r)}$$



α = absorption coefficient in the absence of current injection.

N_T = carrier density at transparency: the rate of absorption is equal to the rate of stimulated emission (1 incoming photon produces 1 outgoing photon).

Exercise

An InGaAsP amplifier operates at 300 K with the following parameters:

η_{in} =0.5, τ_r = 2.5 ns, $N_0 = 1.25\ 10^{18}$ cm^{-3} (transparency carrier concentration), α_a=600 cm^{-1}, w=10 μm, L=200 μm, *d* =2 μm.

– Calculate the transparency current density.

– Calculate the peak gain coefficient and the amplifier gain when $J = 3.5\ 10^4$ A/cm^2.

– Calculate the injection current required to produce this current density.

$J_T = 3.2\ 10^4$ A/cm^2 γ_p =56.25 cm^{-1} G=3.08 i=0.7 A

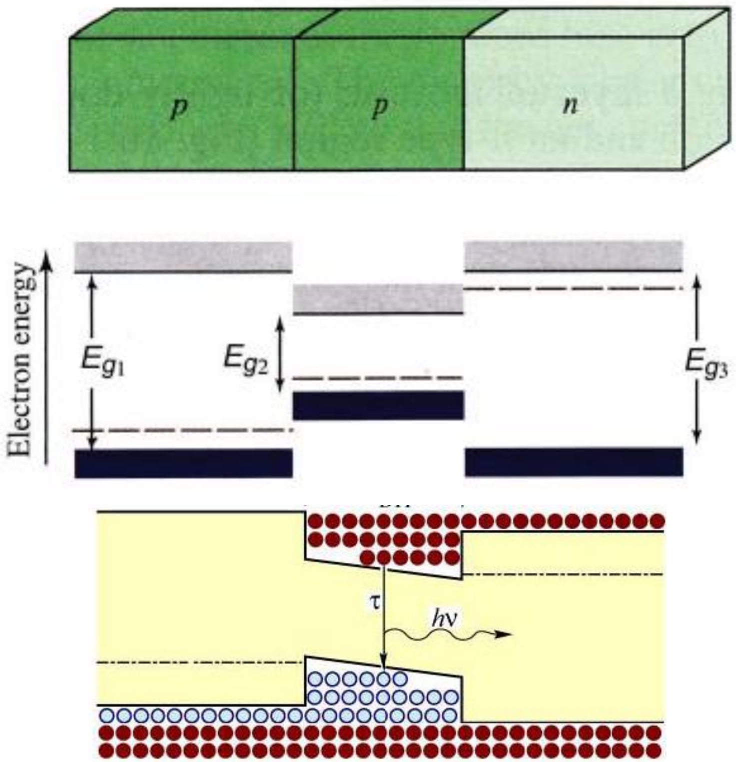
Amplifier threshold and active region thickness

$$J_T = e\, d\, N_0 / (\eta_{in}\, \tau_r)$$

- N_0 is the carrier concentration for transparency.
- J_T is proportional to the **active region thickness** (d).
- Reducing d will reduce the threshold current.
- However, **carrier diffusion** prevents from confining electrons and holes in too small regions (their diffusion lengths are several μm).
- Can we confine the carriers to a region whose thickness is smaller than the carrier diffusion length?
- Yes. By using "**hetero-structures**".
- The second-generation of semiconductor lasers were hetero-structures.

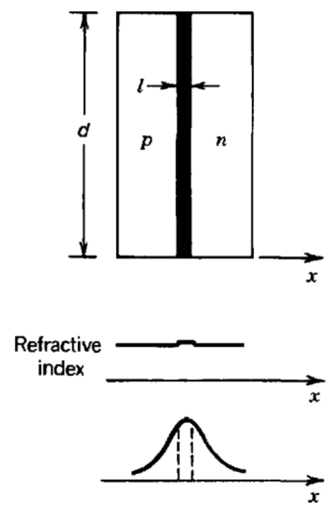
Double Heterostructures (DH)

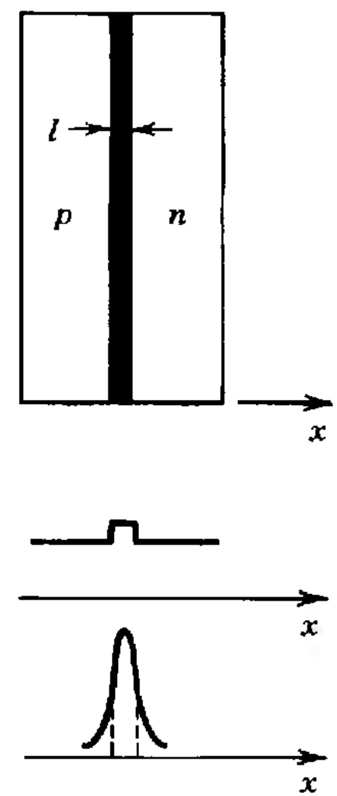
Semiconductors with different band-gaps: improved e/h confinement



Improved photon confinement: "built-in" waveguide because the semiconductors have different refractive index

p-n junction: the depletion layer acts as a waveguide

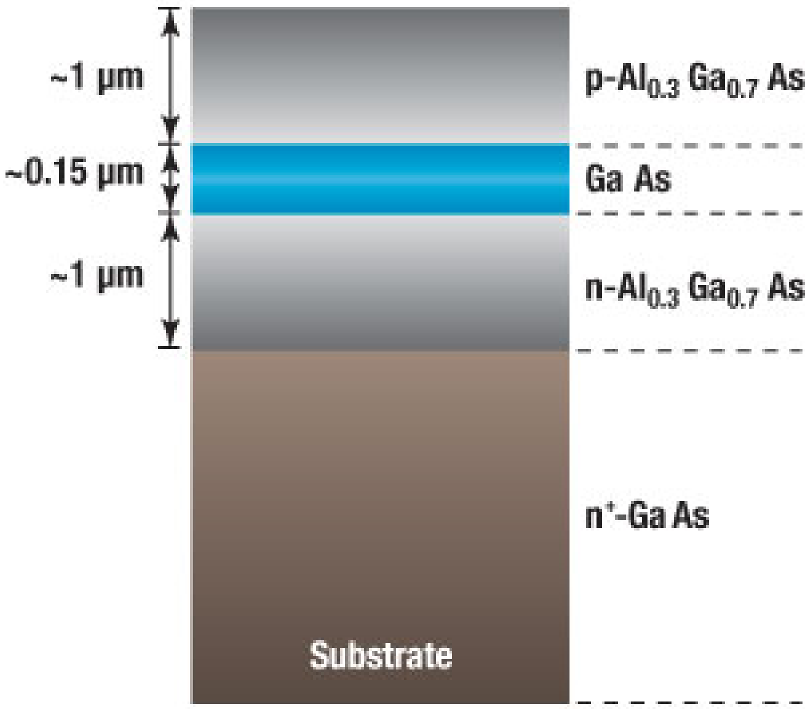




Source: K. Kieu (University of Arizona)

Example of DH structure

- **Improved photon confinement** due to the larger index of refraction of GaAs (n = 3.6) compared to the *p*- and *n*- cladding layers (n = 3.4).
- **Improved carrier confinement** due to the smaller band gap ($E_g \approx 1.5$ eV) of GaAs compared to the *p*- and *n*- cladding layers ($E_g \approx 1.8$ eV).



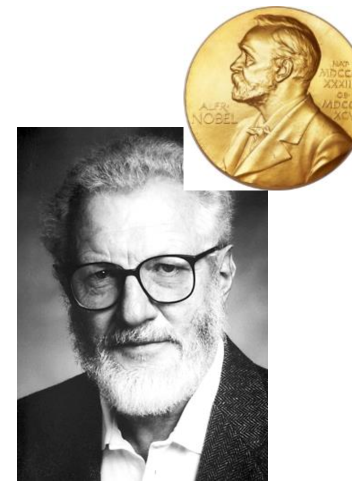
Source: Thorlabs tutorial

The 2000 Nobel Prize in Physics

The improved photon – electron/hole confinement of DH lasers allowed for cw RT emission, enabling the development of technologies with huge social impact.

"For basic work on information and communication technology"

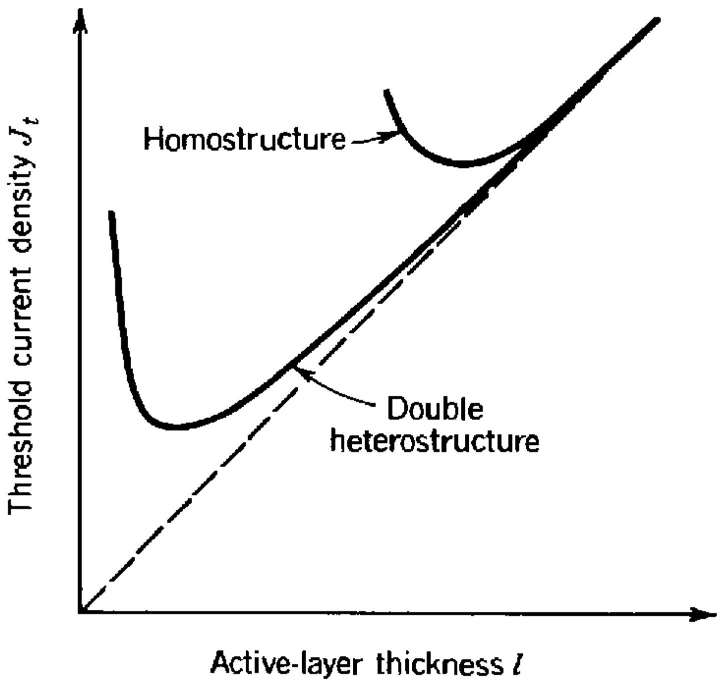
"For developing ***semiconductor heterostructures*** *used in high-speed opto-electronics"*



Zhores I. Alferov
Iaffe Physico-Technical Institute, St. Petersburg Russia

Herbert Kroemer
University of California USA

DH technology: lower threshold



Drawback: DHs are more complicated to fabricate: they require **strict matching** conditions between the two semiconductor layers (the **lattice constant** and the **thermal expansion coefficient**).

Early 1980s: moving the DH technology one step further to quantum-wells (QWs)

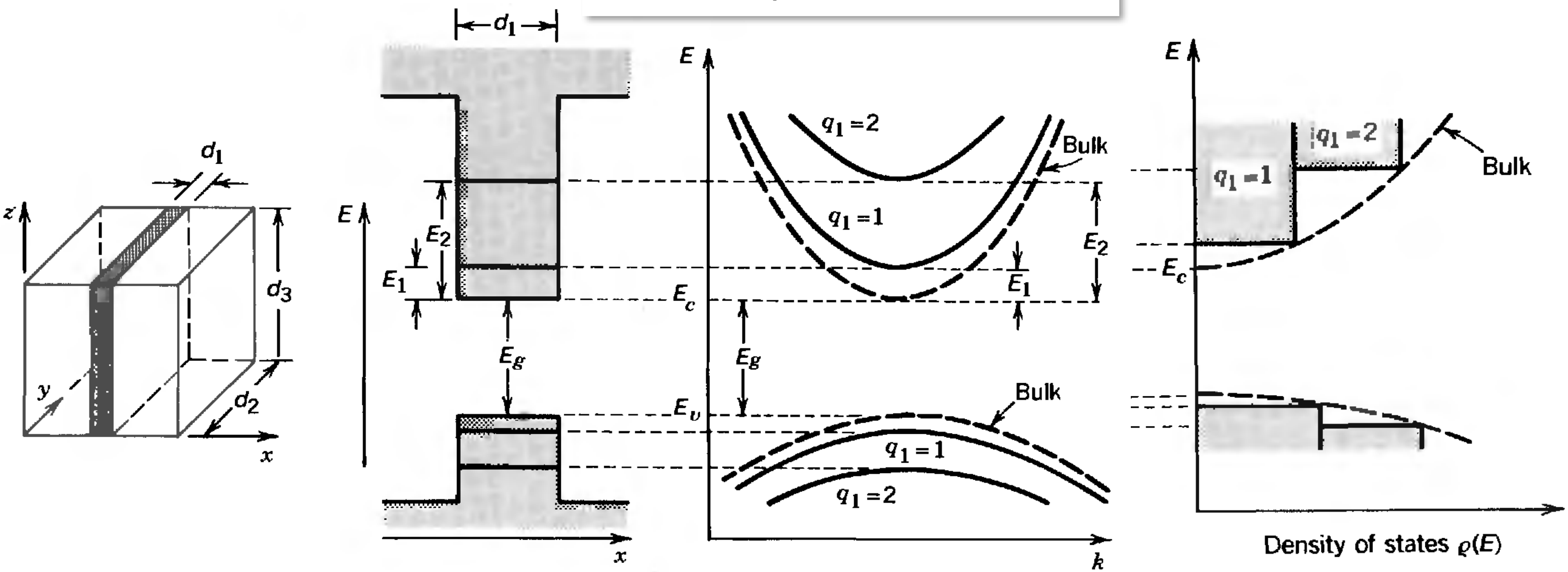
QW lasers are DH lasers (also referred to as “bulk” lasers) but the **thickness** of the active layer is **so narrow** (< 50 nm) that the energy-momentum relation of bulk material does not apply.

- Compared to a DH, a QW has very poor optical wave-guiding ability because of its small thickness.
- Using multiple quantum wells (MQWs) helps to improve optical wave-guiding.
- To have really good optical confinement, separate confinement hetero-structures are used.

QW energy levels

1D infinite potential:

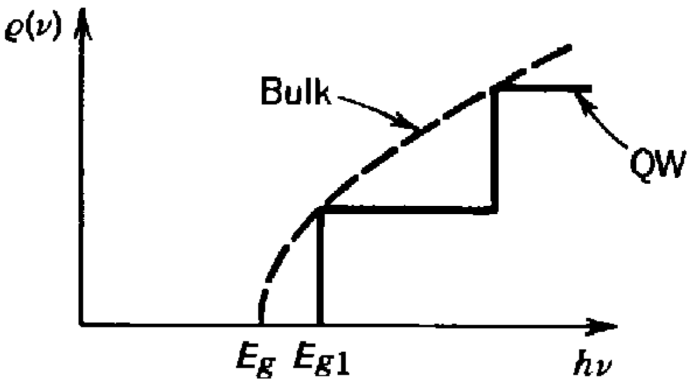
$$E_q = \frac{\hbar^2 (q\pi/d)^2}{2m}, \qquad q = 1, 2, \ldots$$



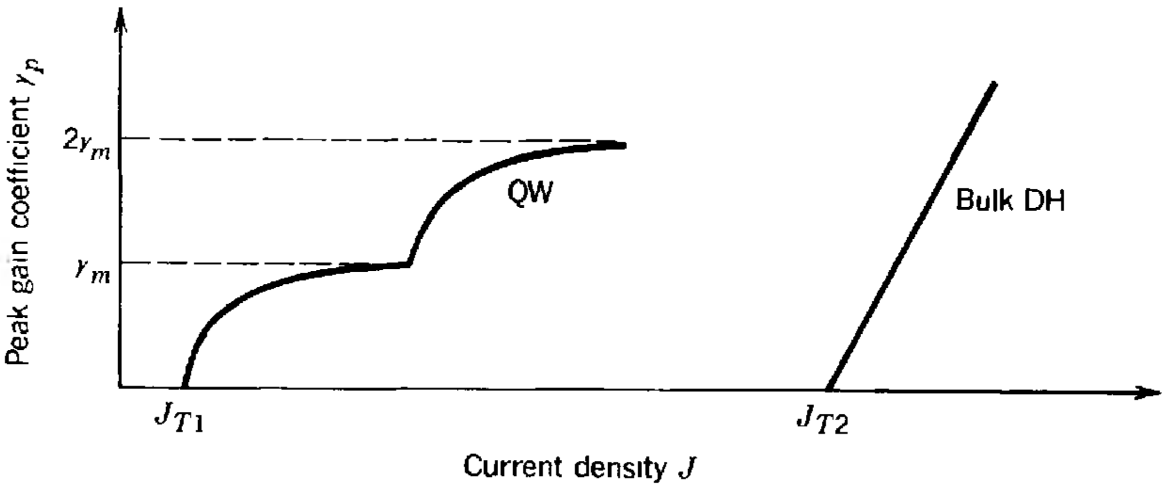
In a QW laser the carriers are confined in the x direction within a distance d_1 (well thickness). But, in the plane of the active layer (y—z plane), they behave as in a bulk semiconductor.

Gain coefficient: QW vs DH

Density of states



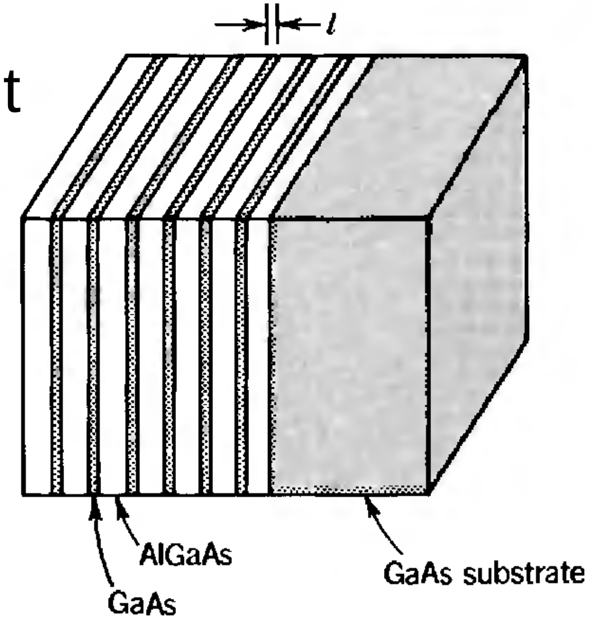
Peak gain coefficient



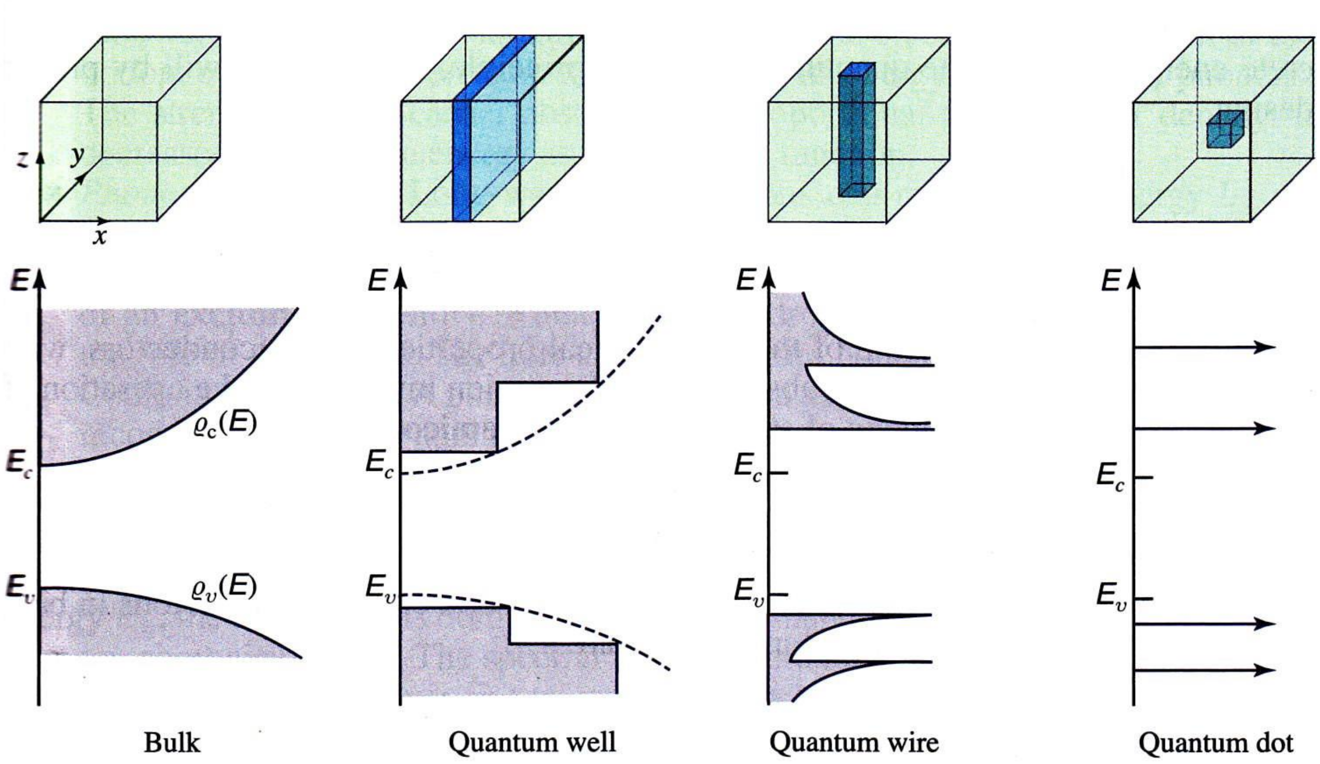
In QWs J_T is several times smaller than comparable DHs.

Multiple Quantum Well (MQW)

- Alternating QW material (narrow band gap) with barrier material (high band gap).
- Advantages:
  - Dramatic reduction in threshold current
  - Reduction in carrier loss
  - Reduced temperature sensitivity of threshold current
  - Increase laser efficiency
  - Reduce thermal resistance
  - Higher output power
- Drawback: increased fabrication cost



Novel materials include quantum-wire, quantum-dash and quantum-dots



Quantum dots: discrete electronic energy states yield atom-like optical transitions.

Fabrication techniques

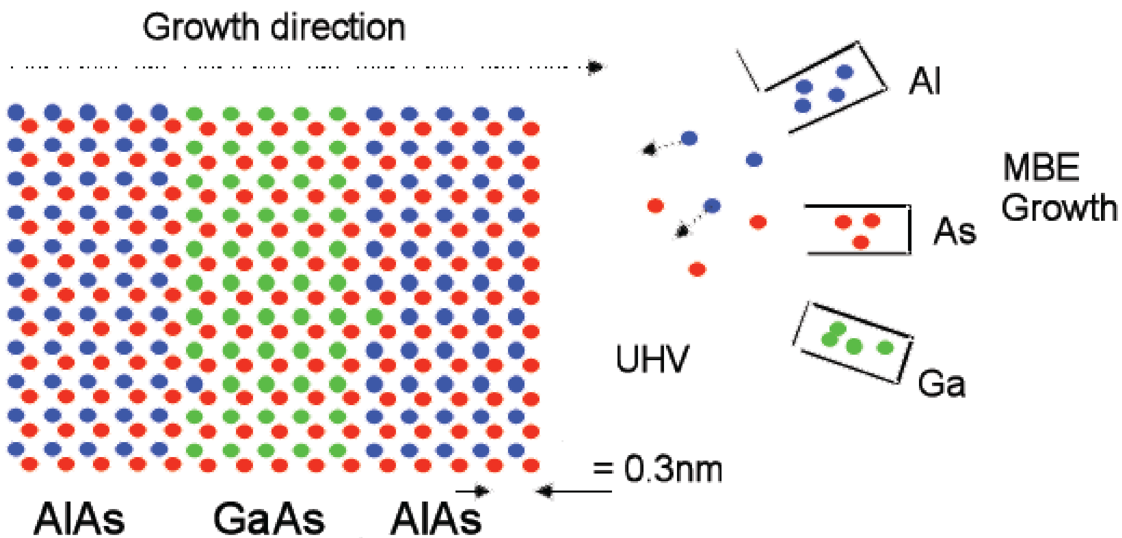
Epitaxial grow, as layers of one material over another, by

- molecular-beam epitaxy (MBE) uses **molecular beams** of the constituent elements in a high-vacuum environment (10^{-8} Pa),
- liquid-phase epitaxy (LPE) uses the **cooling of a saturated solution** containing the constituents in contact with the substrate (but layers are thick),
- vapor-phase epitaxy (VPE) and metal-organic chemical vapor deposition (MOCVD) use **gases in a reactor**. The growth is by chemical reaction (not as MBE, by physical deposition).

Advances in these techniques were crucial for lowering fabrication costs.

Molecular-beam epitaxy

Alfred Y. Cho



"spray painting... with atoms" (The New York Times, 1982)

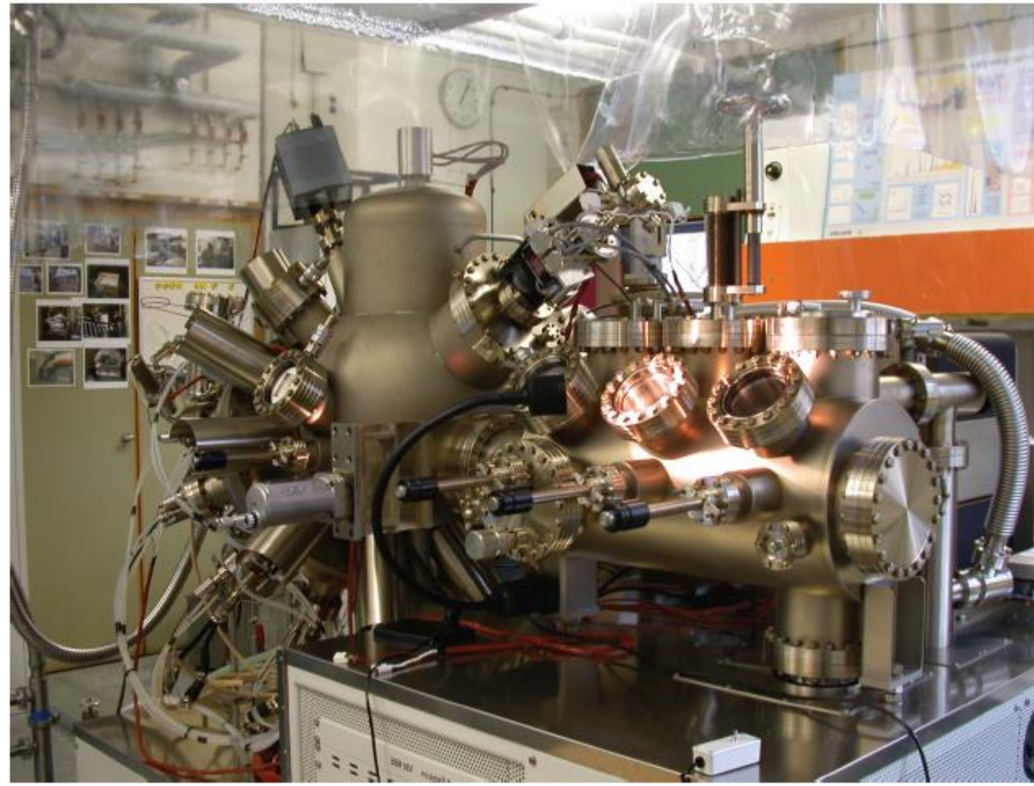
The compositions and dopings of the individual layers are determined by **manipulating the arrival rates** of the molecules and the **temperature** of the substrate surface.

Individual layers can be made very thin (atomic layer accuracy)

Source: J. Faist, ETHZ

Molecular-beam epitaxy

Figure 1 Al Cho (right) and Charles Radice working on an early MBE machine at Bell Labs in 1970.



Adapted from J. Faist, ETHZ

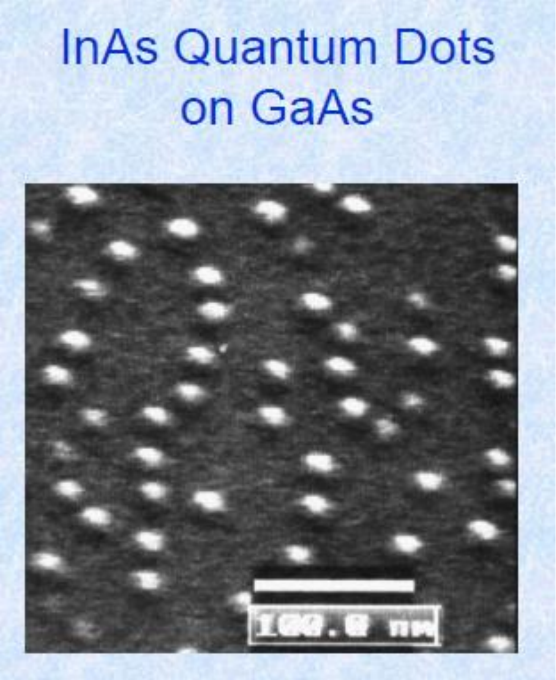
nature nanotechnology | VOL 2 | MAY 2007 |

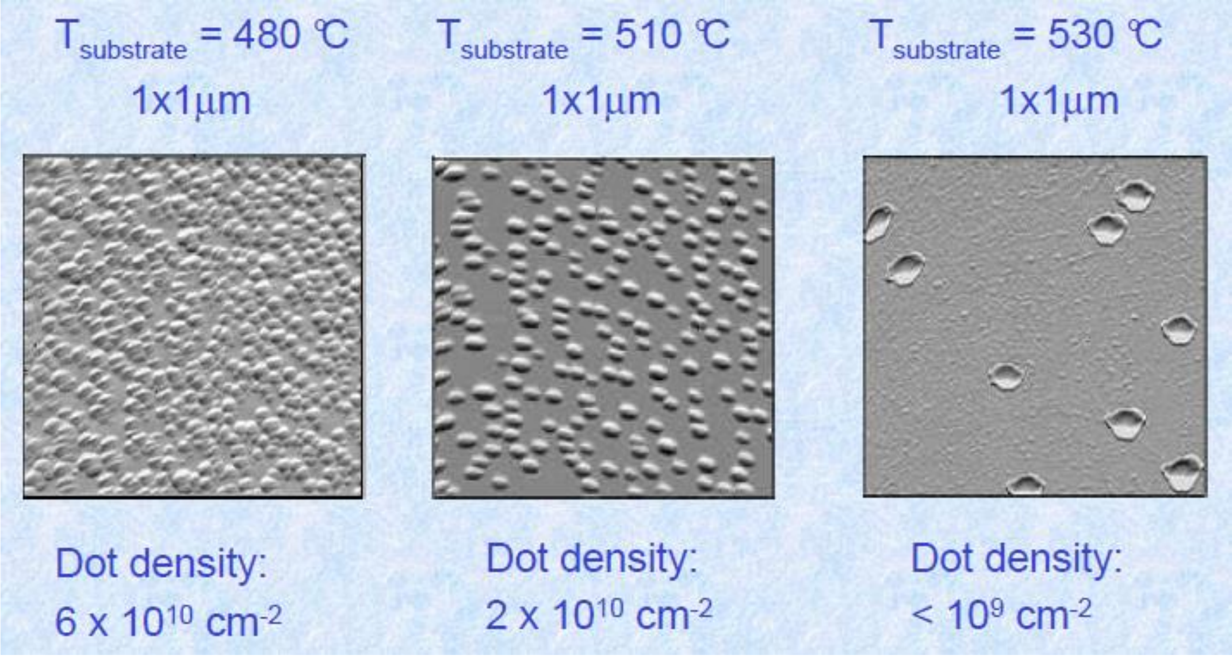
ATG (Asaro-Tiller-Grinfeld) instability

- Also known as the Grinfeld instability.
- It is an elastic instability that often occurs during MBE, when there is a mismatch between the lattice sizes of the growing film and of the substrate.
- Elastic energy is accumulated in the growing film, and at some critical height, the film breaks into isolated islands.
- The critical height depends on mismatch size, among other parameters.
- This instability is used for fabricating **self-assembling quantum dots**.

Self-assembling quantum dots

- Atom-like islands of 10-20 nm diameter, each one containing about 10^5 atoms
- The size and density of QDs determine the emitted wavelength and can be controlled by growth parameters.





Brighter Tutorials: http://www.ist-brighter.eu

TF test

- ❑ The LED operation principle is based on stimulated recombination.
- ❑ The LED operation principle is based on electro-luminescence.
- ❑ The external quantum efficiency is the flux of emitted photons over the flux of injected electrons.
- ❑ Blue LEDs are based on gallium nitride (GaN).
- ❑ Both, LEDs and amplifiers have a threshold; for injection currents above the threshold the gain is large enough to overcome absorption.
- ❑ The threshold condition of an amplifier is when the material is transparent.
- ❑ The threshold is independent of the thickness of the active layer.
- ❑ DH-structures allow confining the carriers in a region that is smaller than the carrier diffusion length.
- ❑ Homo-structures and hetero-structures have similar thresholds.

Outline

- Introduction
- Semiconductor materials
- Photons in semiconductors
- Semiconductor light sources
  - LEDs
  - Amplifiers
  - **Semiconductor lasers**

Outline: semiconductor lasers

- Fabrication
- LI curve (efficiency, threshold)
- Characteristics (optical spectrum, thermal effects)
- Types of semiconductor lasers
- New materials and cavity designs

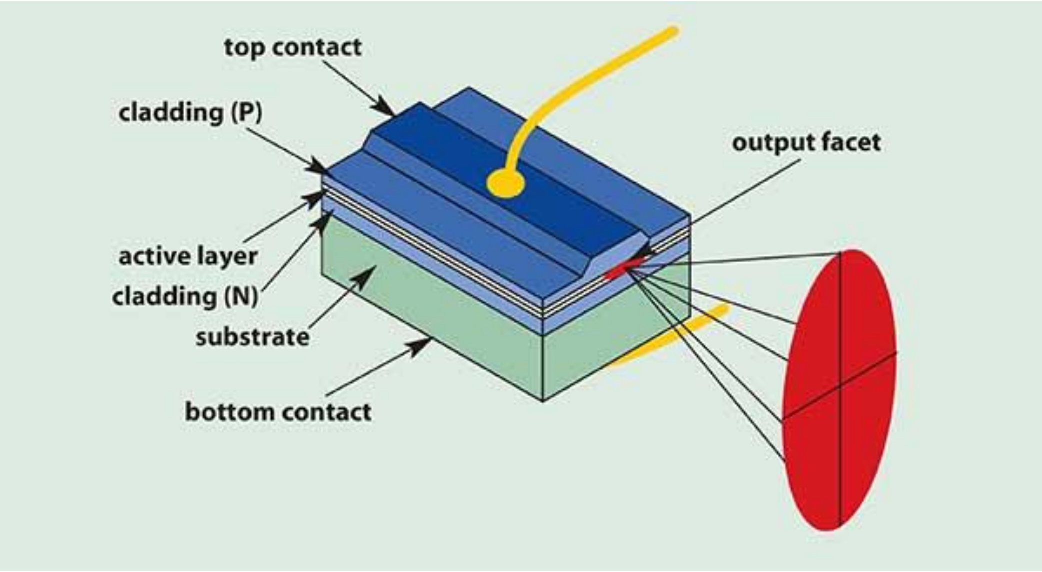
Semiconductor laser = laser diode = semiconductor material + optical cavity

The **simplest** cavity: Fabry-Perot (FP), formed by the cleaved facets of the semiconductor material.

Edge-Emitting laser (EEL)

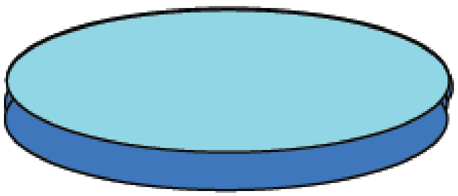
Fabrication steps:

- epitaxial growth,
- wafer processing,
- facet treatment,
- packaging.

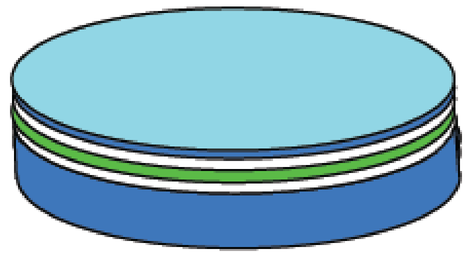


Source: photonics.com

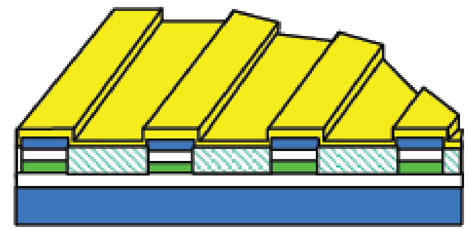
FABRICATION STEPS FOR A SEMICONDUCTOR LASER



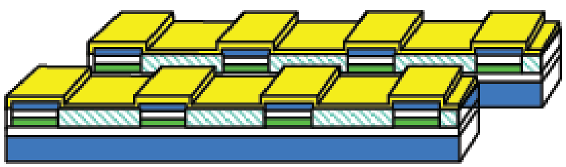
1- SUBSTRATE



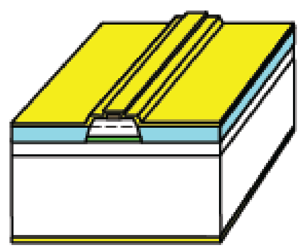
2- EPITAXIE



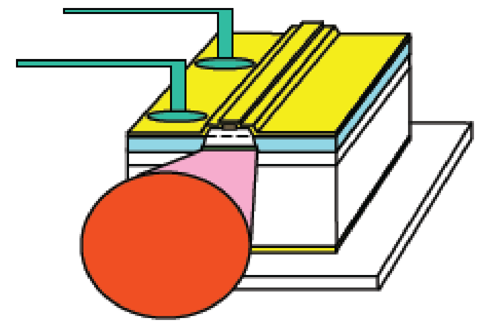
3- LASER PROCESSING



4- FACETS CLEAVING



5- SINGLE CHIP PREPARATION

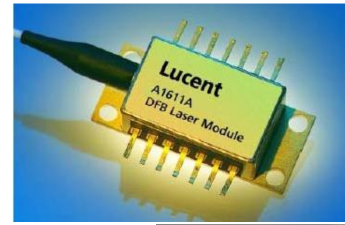


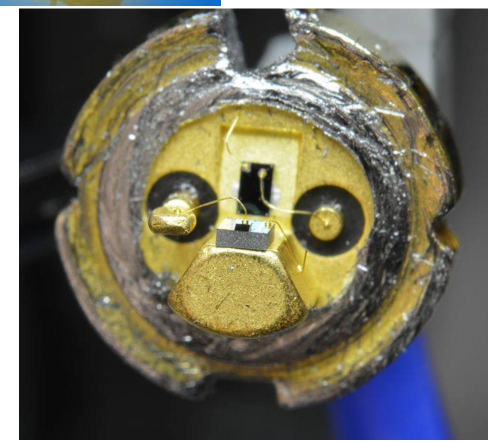
6- MOUNTING, BONDING

Source: J. Faist, ETHZ

The final step: packaging

- Allows **integrating laser diodes in devices**
  - Mechanical and optical coupling to an optical fiber.
  - Temperature stabilization.
  - Photodiode for monitoring of the optical power.
  - Optical Isolation to avoid back reflections.
- **Increases the fabrication cost**.





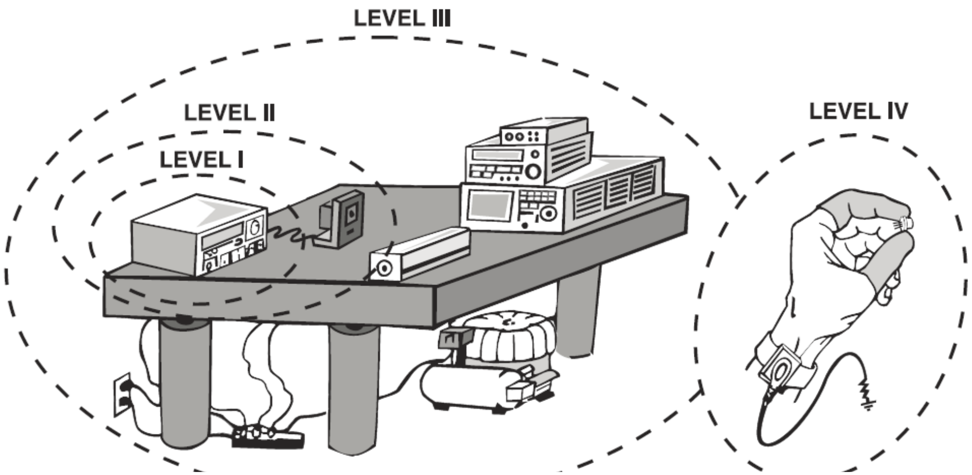
A laser diode with the case cut away. The laser diode chip is the small black chip at the front; a photodiode at the back is used to control output power.

Source: Wikipedia

Main problems with laser diodes in the lab

- It’s been said that there are two types of researchers - those who have blown a laser diode and those who will.

- Main problems: electrical transients and electrostatic discharge.



Current source

Temp. controller

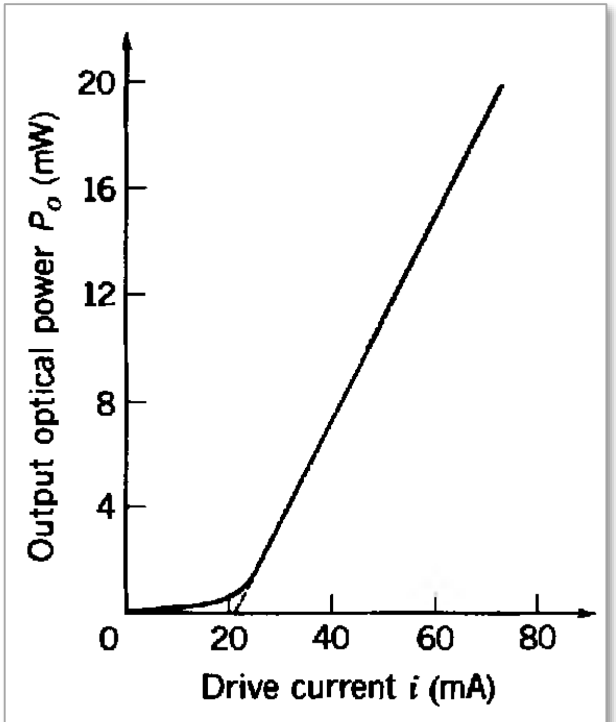
4-Tier Laser Protection Strategy		
LEVEL	**Description**	**Damage mechanism**
I	Instrumentation (Current source, Temperature controller)	Over-current, overheating, power line surges and spikes (transients)
II	System setup (Cables and mounts, Proper grounding, Shielding)	Radiated electrical transients
III	Lab environment, Power line conditioning, Other instruments	Severe fast transients
IV	Laser packaging, Handling, and Human contact	Electrostatic discharge (ESD), Foreign-matter contamination

Review

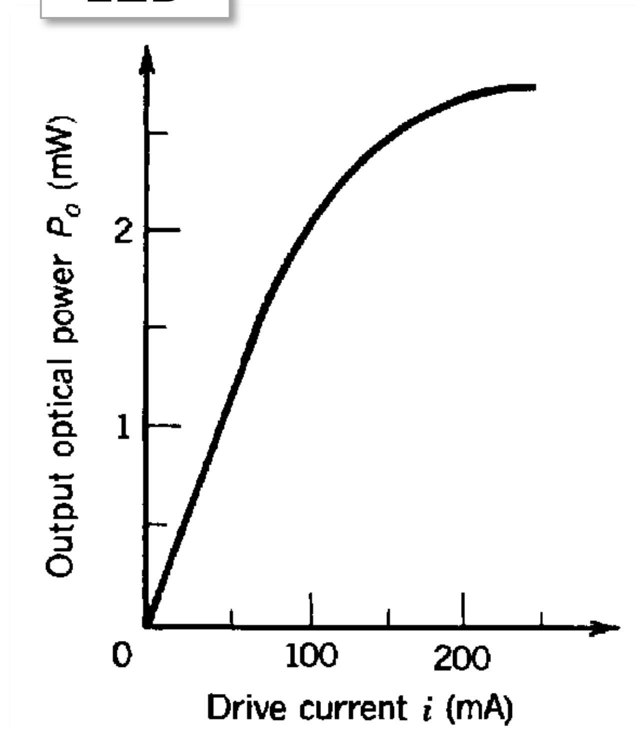
- Heterostructures are much more efficient than homojunctions.
- Due to potential barriers at the boundary of semiconductors with different bandgap widths, the regions of recombination and light emission, coincide and are concentrated entirely in the “active” layer.
- Because of difference in the refractive index, light is concentrated in the active layer.
- Trying to find the “ideal couple” was a very difficult problem and the patent for the DH laser was initially viewer as a “paper” patent.
- Which couple? Ga As popular because
  - “direct” band structure
  - wide energy gap
  - effective radiative recombination
  - high mobility
- Good candidate for “partner” material (close values of the lattice constant): AlAs.
- But AlAs was known to be chemically unstable and decompose in moist air.
- But AlGaAs turned out to be chemically stable and suitable for preparation of durable heterostructures.
- AlGaAs heterostructures were used for the first RT lasers and became the basis for modern optoelectronics.

LI curve: diode laser vs LED

Diode laser



LED



Note the different scales

Power conversion efficiency (PCE)

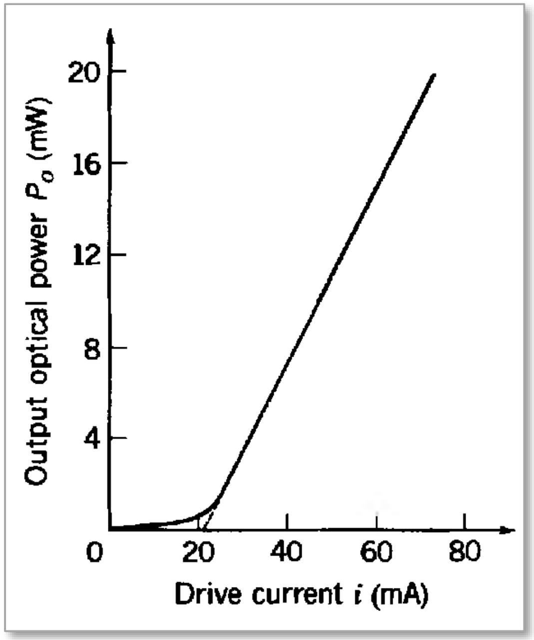
- Is the **slope** of the LI curve,

  PCE =$\Delta P_0/\Delta I$

- Typically 50% at 50 C.

- Other efficiency measures:
  - quantum efficiency
  - overall efficiency

LI curve



Thermal effects at high currents lead to saturation (more latter)

Wall-plug efficiency: optical output power / input electrical power

Quantum efficiency

- Laser optical power: $P= h\nu\ \Phi$ (in Watts)

  Φ : flux of emitted photons (photons per unit time).

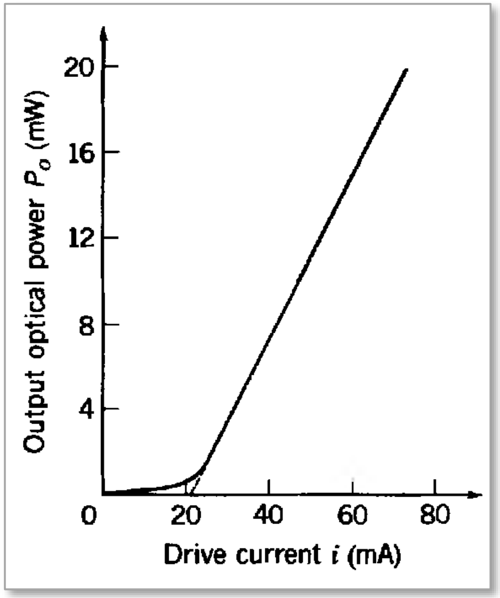
- $\Phi = \eta_d\ (I-I_{th})/e$ (I, I_{th} in amperes)

  η_d : quantum efficiency. It accounts for the fact that only a fraction of the electron-hole recombinations are radiative (internal efficiency) + only part of the emitted photons are useful (emission efficiency)

  $\Rightarrow\ P = h\nu\ \eta_d\ (I-I_{th})/e = 1.24\ \eta_d\ (I-I_{th})/\lambda$

  Example:

  - I_{th}= 21 mA
  - λ=1.3 μm (InGaAsP)
  - $\eta_d = (\lambda /1.24)\ P/(I-I_{th})=0.4$



Overall efficiency

- Ratio of optical power to electrical power, $\eta = P/IV$
- $P = (h\nu/e)\ \eta_d\ (I-I_{th})$
- $V = V_k + R_d I$

  V_k is the kink voltage (related to the separation of quasi-Fermi energies)

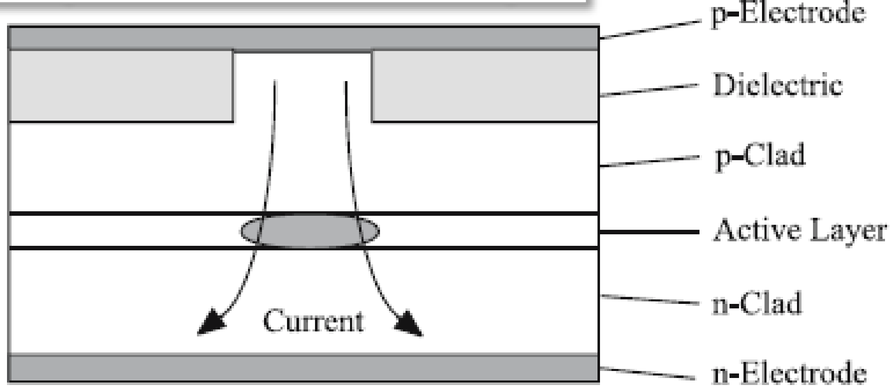
  $R_d = dV/dI$ is the differential resistance

- $\eta = (h\nu/e)\ \eta_d\ (I-I_{th})\ /I(V_k + R_d I)$
- η is a function of the injected current, I
- The efficiency is maximum when

$$\hat{I}_c = I_{th} \cdot \left(1 + \sqrt{1+\xi}\right) \quad \text{with} \quad \xi = \frac{V_k}{I_{th} R_d}$$

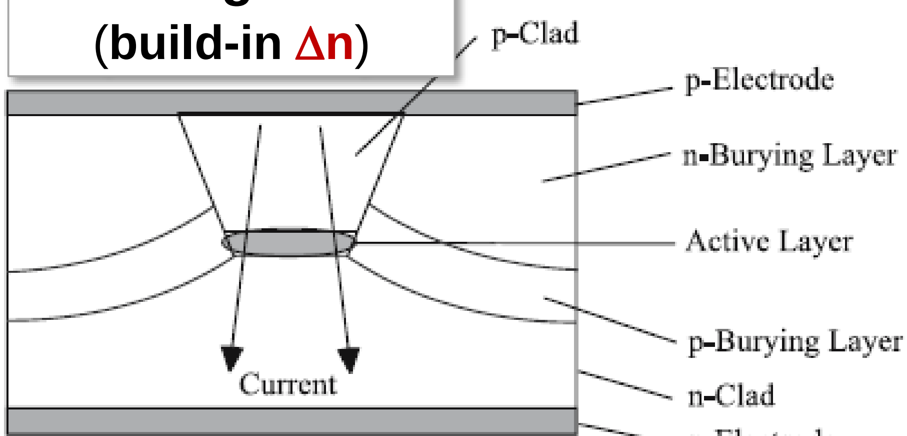
To further reduce the threshold: lateral confinement

Gain guided
(carrier induced Δn)

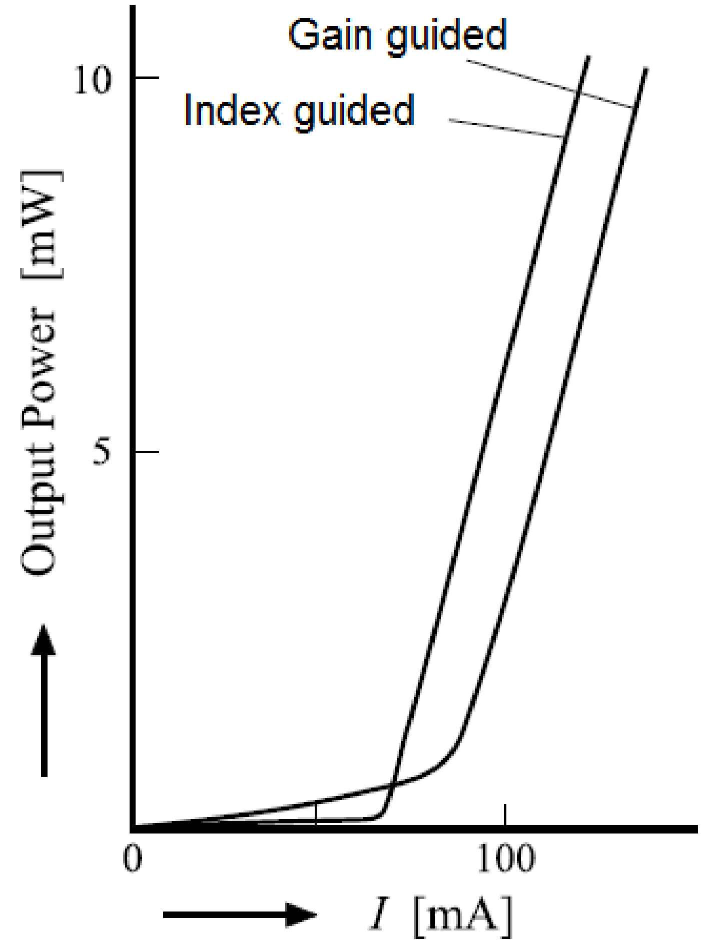


(a)

Index guided
(build-in Δn)

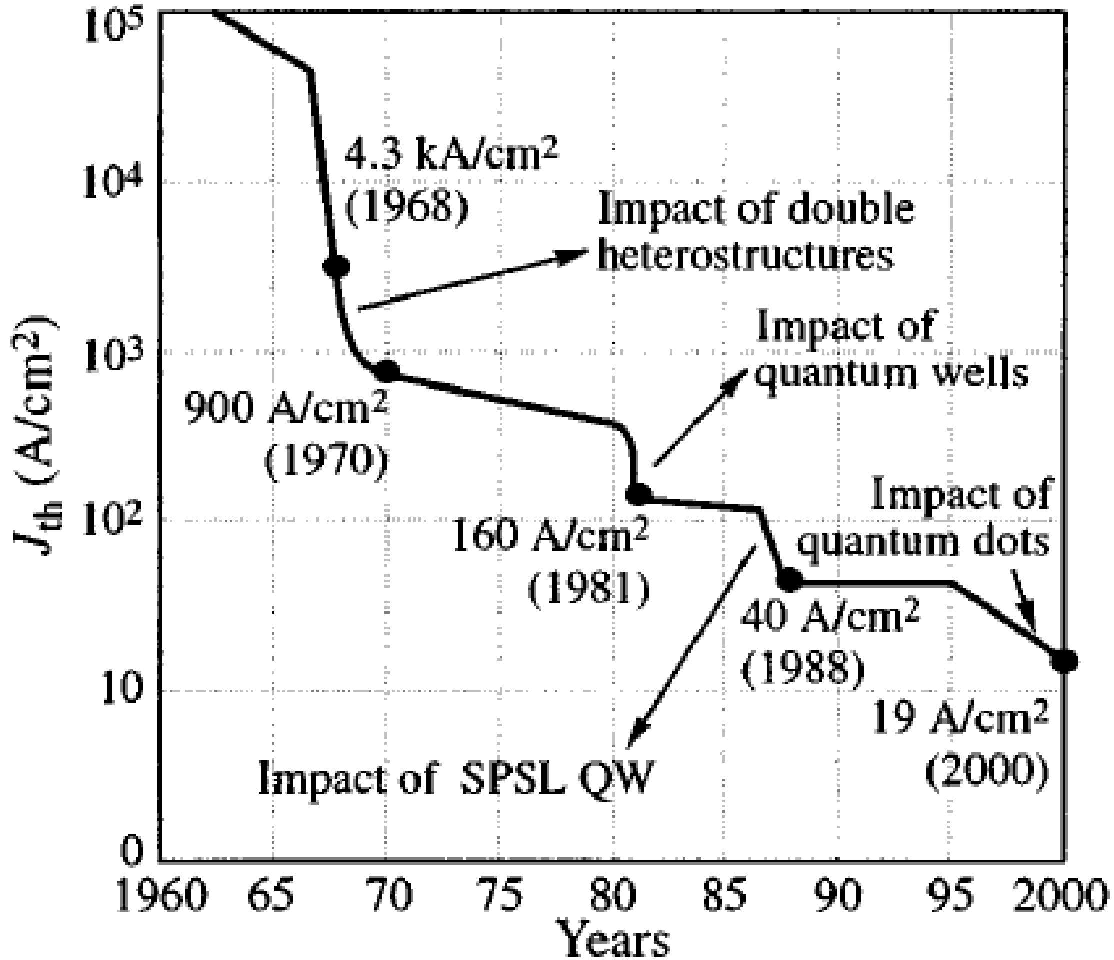


(b)



Source: J. Ohtsubo

The history of semiconductor lasers is the history of the campaign to lower the threshold current



SPSL: short-period superlattices (see quantum-cascade lasers)

Source: Z. Alferov IEEE JSTQE 2000

2020: threshold-less lasers

Research Article
Vol. 2, No. 1 / January 2015 / *Optica* 66
optica

Near thresholdless laser operation at room temperature

I. Prieto,[1,2] J. M. Llorens,[1] L. E. Muñoz-Camúñez,[1] A. G. Taboada,[1,2] J. Canet-Ferrer,[3] J. M. Ripalda,[1] C. Robles,[1] G. Muñoz-Matutano,[3,4] J. P. Martínez-Pastor,[3] and P. A. Postigo[1,*]

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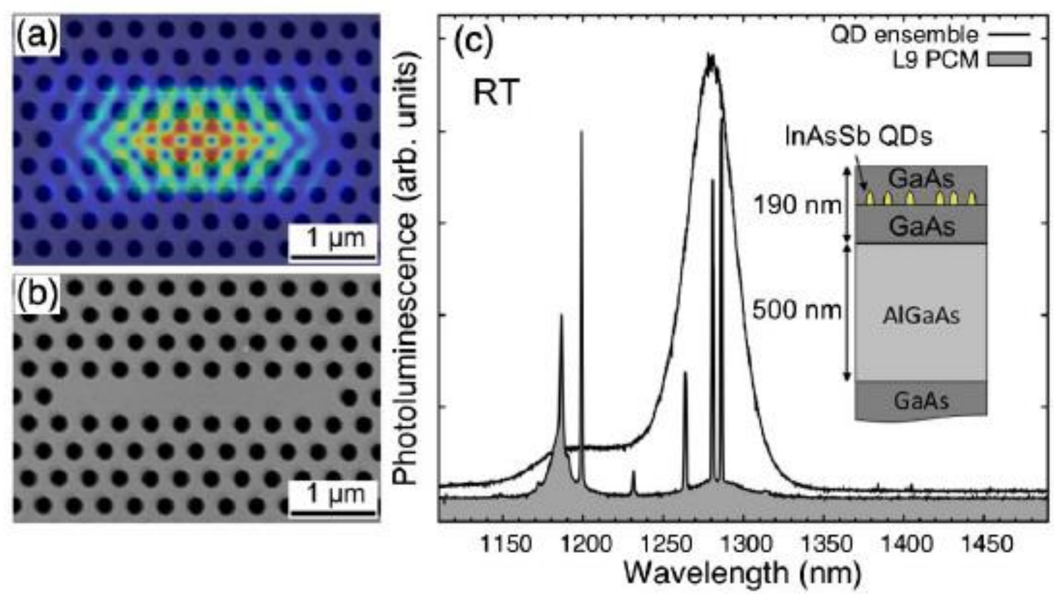
(a) Calculation of the electric field distribution of the fundamental mode.
(b) Scanning electron microscopy image of a L9 photonic-crystal Microcavity (PCM).
(c) PL of the ensemble of the QDs outside of the PCM (black line) and PL of a L9-PCM (filled gray) showing the mode structure. The inset shows a schematic diagram of the epitaxial material.



Emission characteristics: how many modes?

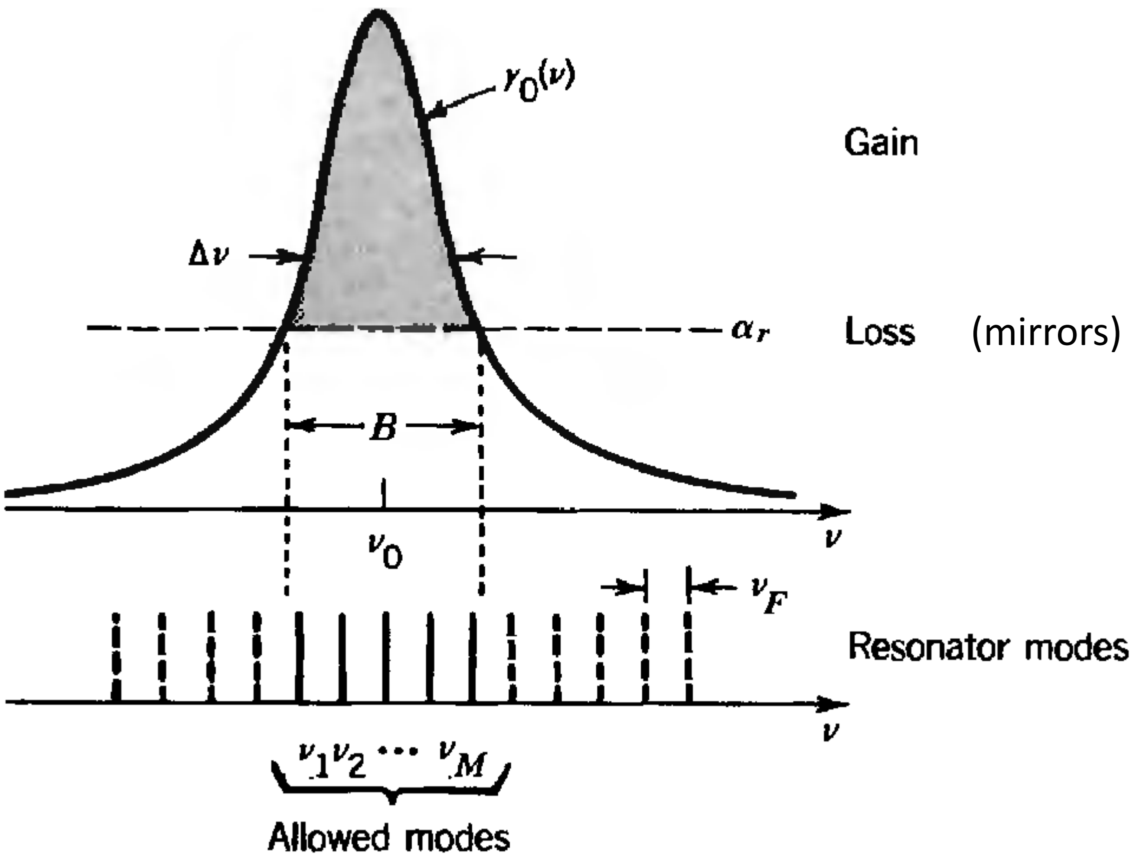
- The semiconductor gain spectrum is broad
  $\Rightarrow$ **supports many longitudinal modes**.

$\boxed{\nu_m = m\,(c/n)/(2L)}$

$\boxed{\Delta\nu = c/(2nL)}$

$\boxed{\Delta\lambda = (\lambda_o)^2/(2nL)}$

(free-space wavelength spacing, measured with an Optical Spectrum Analyzer)



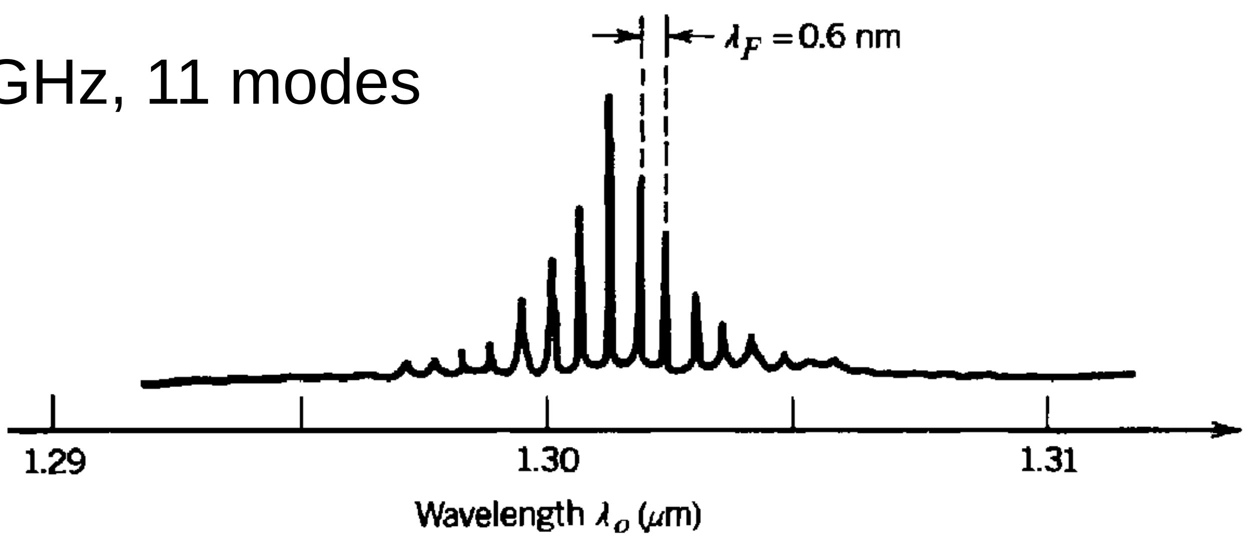
n = 3.5, L = 1 mm:
$\Delta\lambda$ = 0.05 nm @ 635 nm
$\Delta\lambda$ = 0.3 nm @ 1550 nm

Exercise

Consider a InGaAsP (n=3.5) laser with a FP cavity of length L = 400 μm. If the gain spectral width is 1.2 THz, how many longitudinal modes may oscillate? If the central wavelength is 1.3 μm, which is the wavelength spacing?

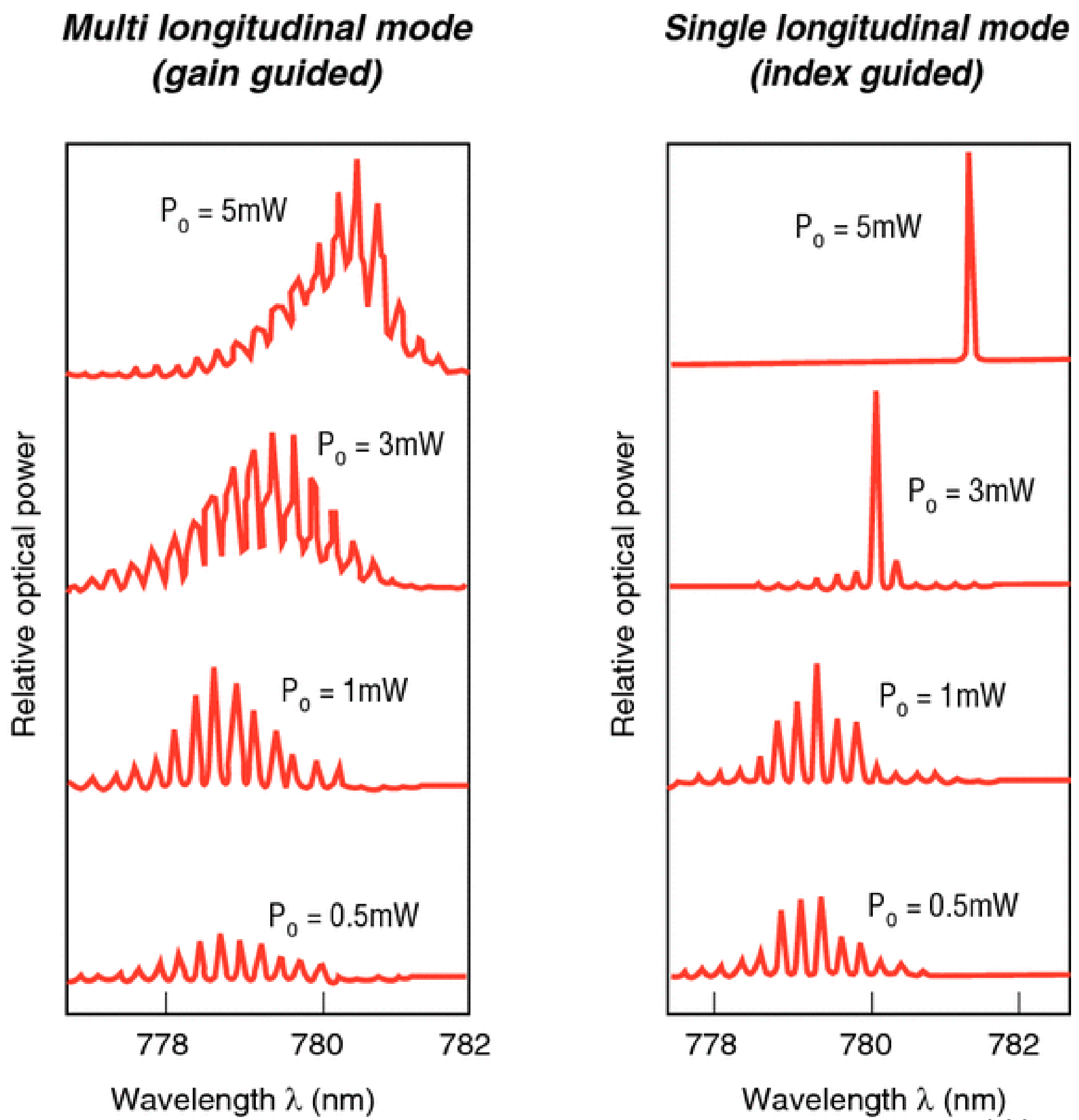
$\Delta\nu = c/(2nL)$ $\Delta\lambda = (\lambda_o)^2/(2nL)$

$\Delta\nu$ = 107 GHz, 11 modes



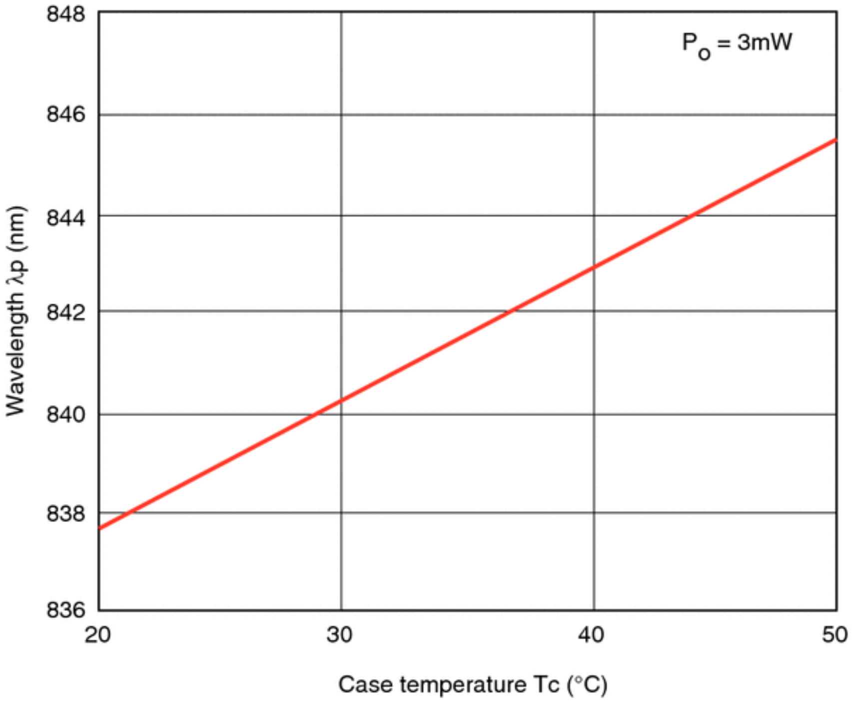
Gain + cavity determine the optical spectrum

- The number of lasing modes and their relative power depends on gain (current and temperature) and on the type of laser.
- It is often possible to adjust I and T for single-mode operation, but it can be achieved over a **limited** I and T range.

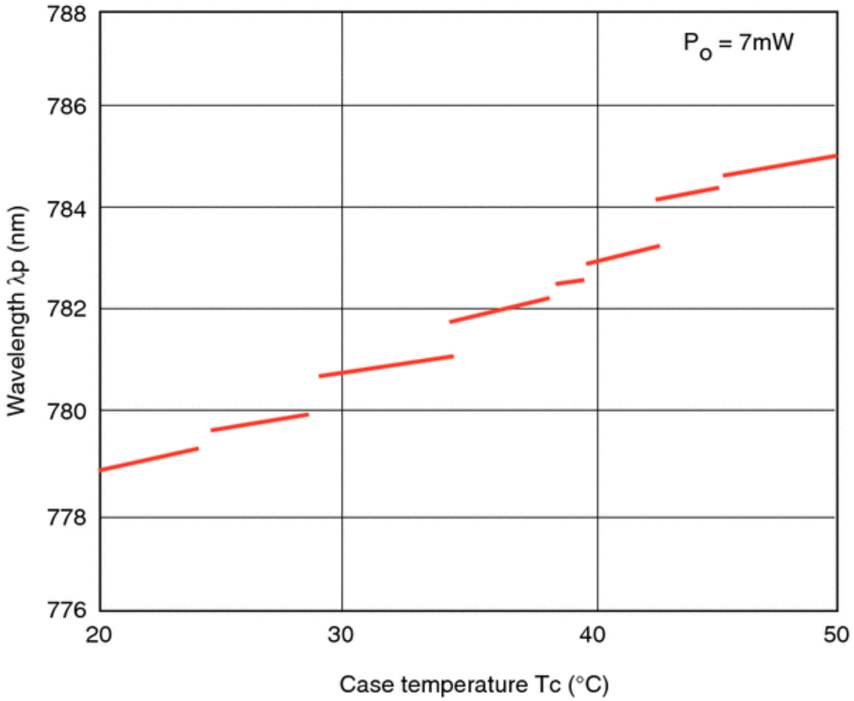


Thermal properties: wavelength tuning

Single-mode laser



Multimode: Mode hopping



~0.4 nm/C

Thermal effects in the LI curve

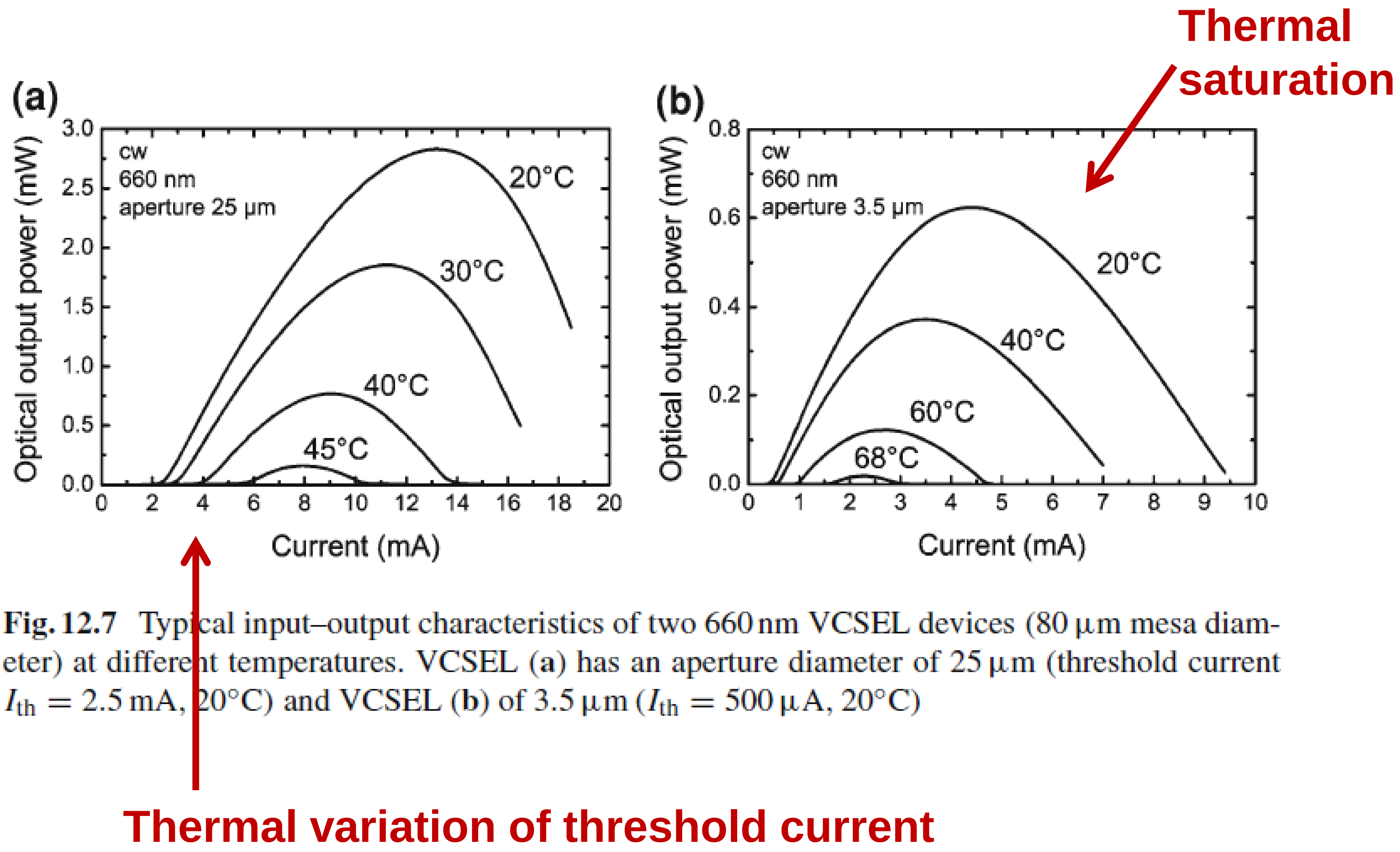


Fig. 12.7 Typical input–output characteristics of two 660 nm VCSEL devices (80 µm mesa diameter) at different temperatures. VCSEL (**a**) has an aperture diameter of 25 µm (threshold current $I_{th} = 2.5$ mA, 20°C) and VCSEL (**b**) of 3.5 µm ($I_{th} = 500$ µA, 20°C)

Source: VCSELs, R. Michalzik

Why thermal variations?

With increasing current, increasing temperature (**Joule heating**).

Temperature affects:

- the gain (the peak and the width)
- the refractive index

Kramers-Kronig: gain $\sim -\,\mathrm{Im}(\chi)$, n $\sim$ $\mathrm{Re}(\chi)$

The temperature modifies the refractive index which in turn modifies the cavity resonance.

Outline: semiconductor lasers

- Fabrication
- LI curve (efficiency, threshold)
- Characteristics (optical spectrum, thermal effects)
- **Types of semiconductor lasers**
- New materials and cavity designs

Types of semiconductor lasers

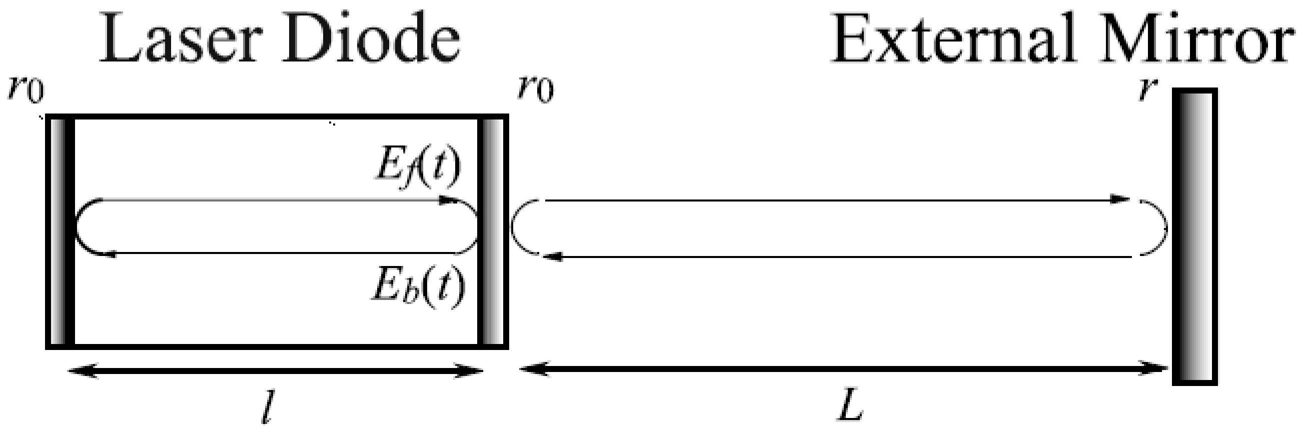
- Emission:
  - single mode
  - multimode
- Cavity:
  - edge emitting
  - vertical cavity
  - ring cavity
- Semiconductor lasers but not diode lasers:
  - Quantum cascade lasers
  - Optically pumped semiconductor lasers

Single-mode lasers

- Single-mode emission is important for optical fiber communications and for applications that require high beam quality.

- Dynamically stable single-mode emission can be achieved by using a **mode-selective cavity**:
  - An **external** mirror – External Cavity Laser (ECL)
  - A **Bragg-Grating** (BG) mirror
    - Distributed Feedback (DFB)
    - Distributed Bragg Reflector (DBR)
    - Vertical Cavity Surface Emitting Lasers (VCSEL)

External Cavity Laser

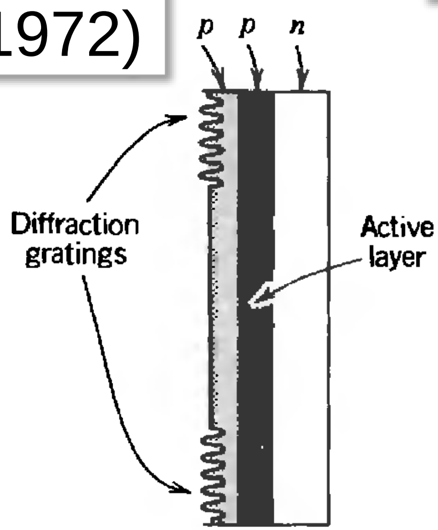


- With controlled feedback conditions the laser emission "locks" to one of the modes of the "compound" cavity. Advantage: decrease of the threshold current (reduced cavity loss) and reduced line-width.
- Drawback: uncontrolled feedback conditions can lead to instabilities and chaotic emission (more latter).

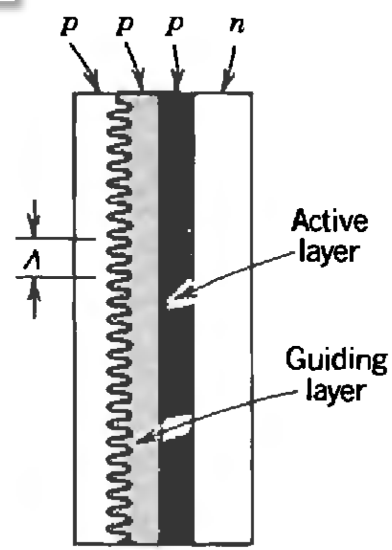
Bragg-Grating (BG) devices

- Peak reflectivity for a specific frequency (the Bragg-frequency) via coherent addition of distributed reflections.

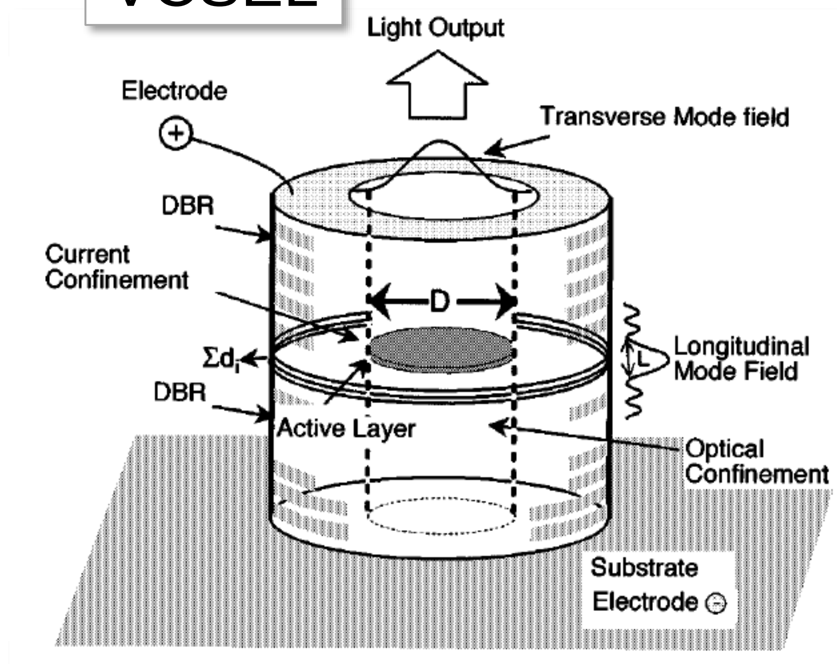
DBR (1972)



DFB

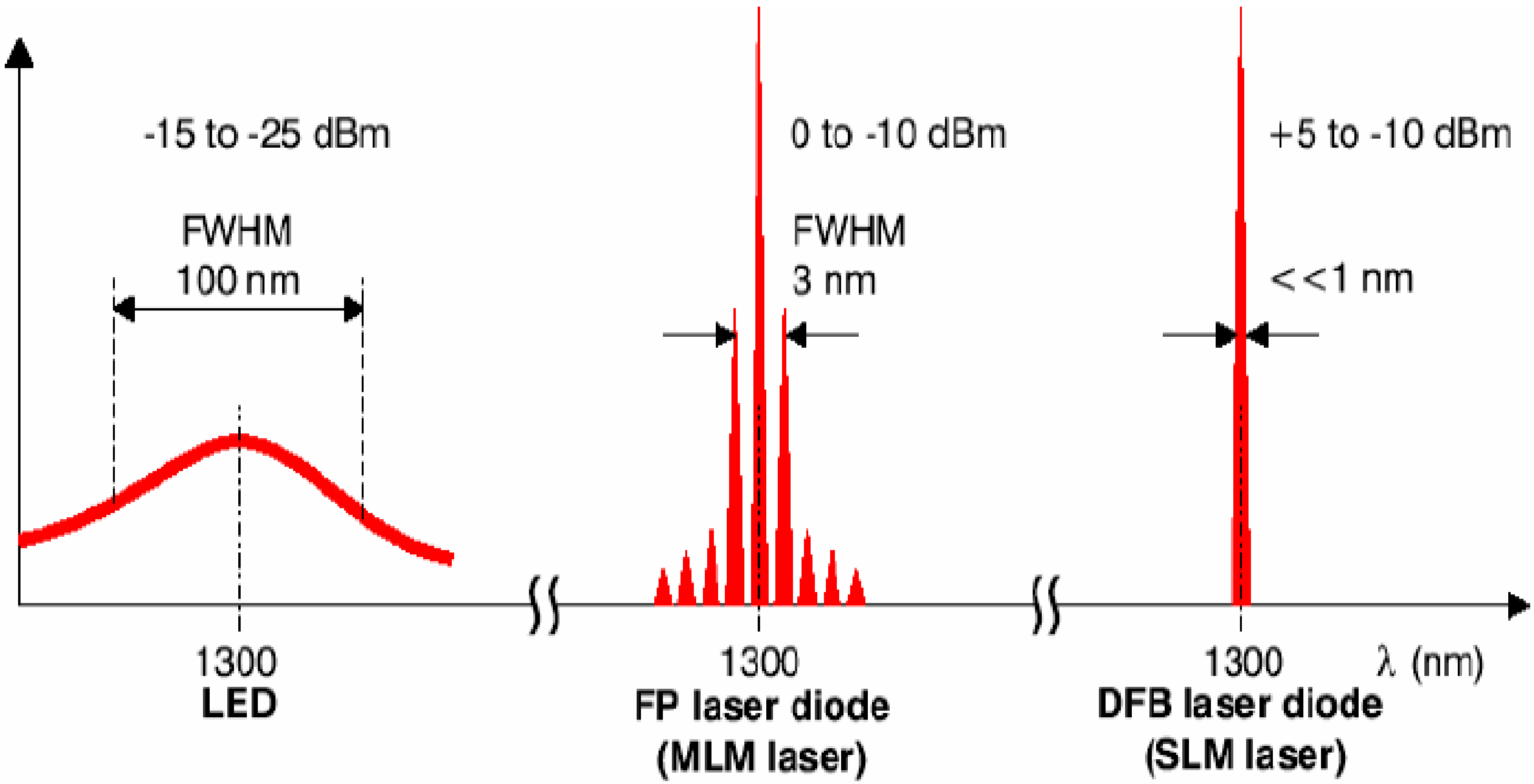


VCSEL



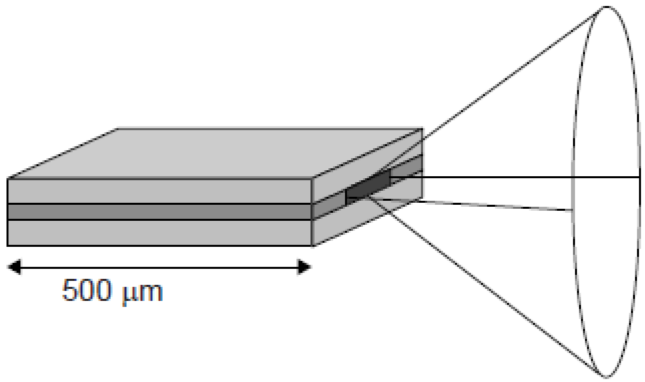
K. Iga, proposed in 1977, RT 1985

Optical spectra



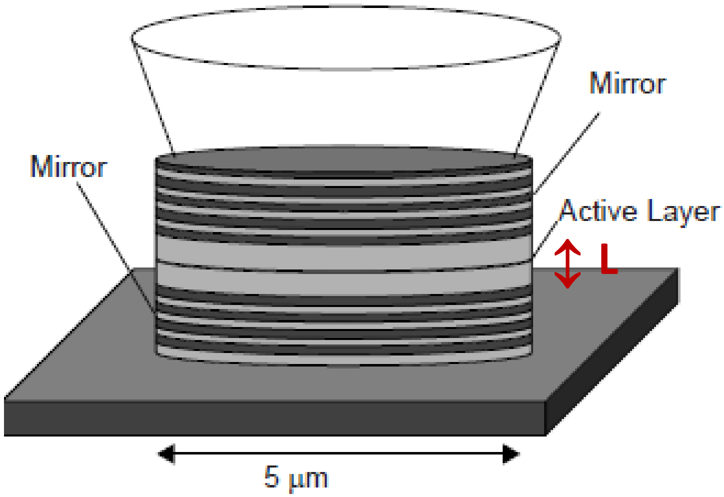
EEL vs VCSEL

Edge-Emitting Laser (EEL)



Wide divergent output

VCSEL



L ≈ 300-500 μm

The semiconductor facets serve as mirrors

Two DBRs serve as mirrors

L=1-10 μm $\Delta\lambda = (\lambda_o)^2/(2nL)$

⇒ **single-longitudinal-mode**.

EELs and VCSELs have very different cavity lengths and mirror reflectivities (~30%, 99%), but **similar photon lifetimes**.

Exercise

InGaAsP (n=3.5) VCSEL laser with L = 5 μm. If the gain spectral width is 1.2 THz, how many longitudinal modes may oscillate? If the DBRs reflectivity is 99%, what is the photon lifetime? Compare with an EEL of L = 400 μm.

$\boxed{\Delta\nu = c/(2nL)}$ $\Delta\nu$ = 8.5 THz, 1 mode

$\boxed{\tau_p = n/(c\alpha_r)}$ α_r= Distributed loss coefficient $\boxed{\alpha_r = \alpha_i - \ln(R_1 R_2)/2L}$

$\boxed{R_1 = r_1^2,\ R_2 = r_2^2}$

$\boxed{\tau_p \approx -(2nL/c)/\ln(R_1 R_2)}$ $\boxed{\tau_p = 3.5 - 6\text{ ps}}$

VCSEL advantages

- **Single-longitudinal-mode**
- Low threshold currents & high efficiency
- **Circular** beam profiles with small divergence angles, simplifying the design of beam-shaping optics.
- High data transmission speed.
- The active diameter of the VCSEL can be reduced to just a few μms in order to obtain single-transverse-mode operation together with lowest threshold currents in the sub-100 μA range.
- It can also exceed 100 μm to get high output powers beyond 100 mW.
- Device testing at the wafer level: **low fabrication cost**.
- Straightforward fabrication of homogeneous **1D and 2D laser arrays.**

Any drawbacks? Yes! Polarization instability, thermal sensitivity & multiple transverse modes (broad-area devices)

Further reading: VCSELs, R. Michalzik (Springer 2013)

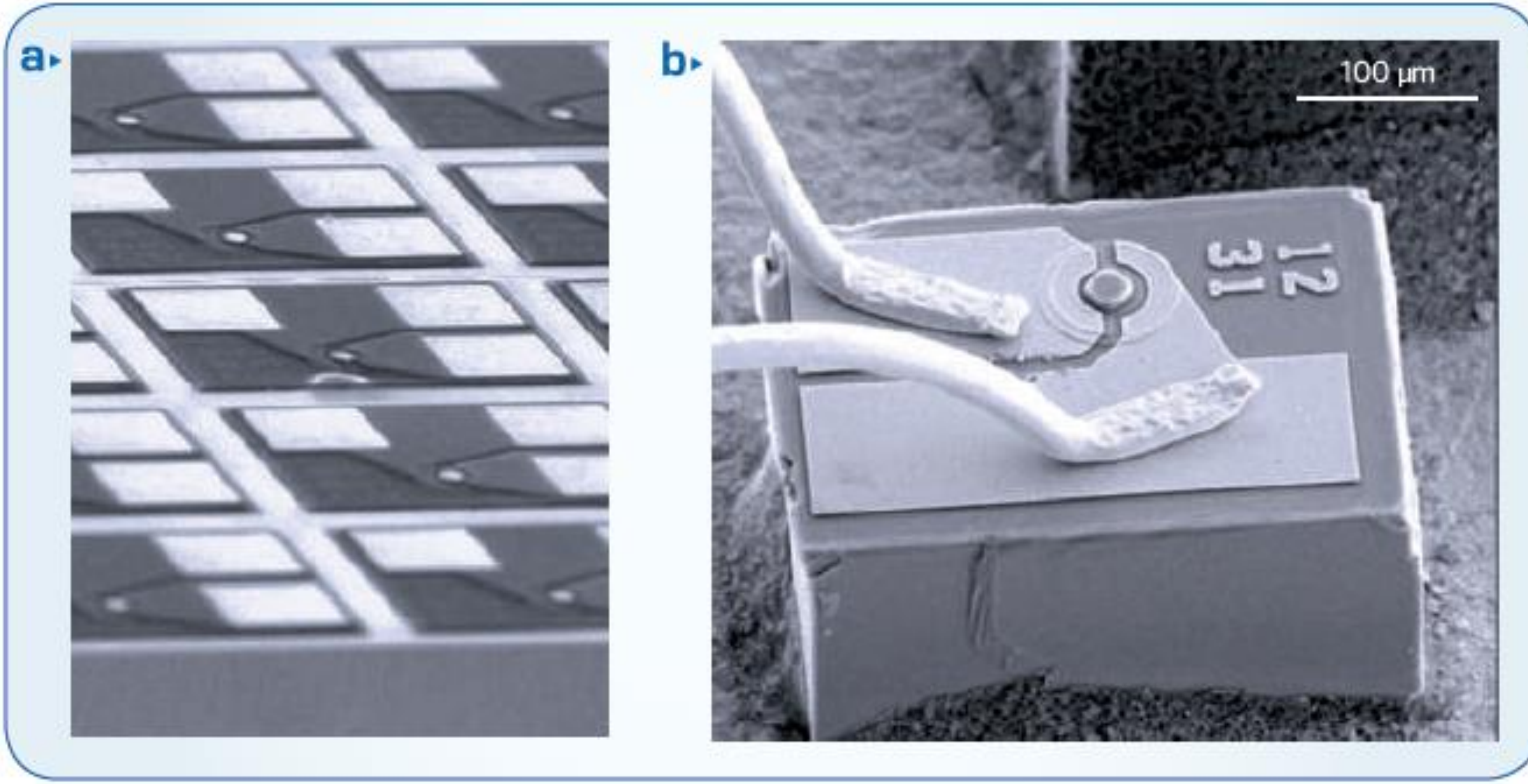
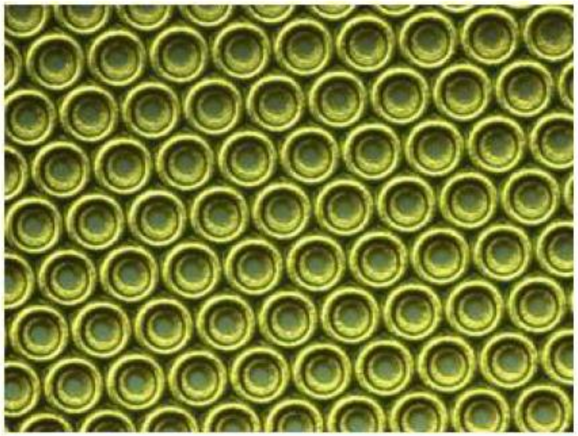


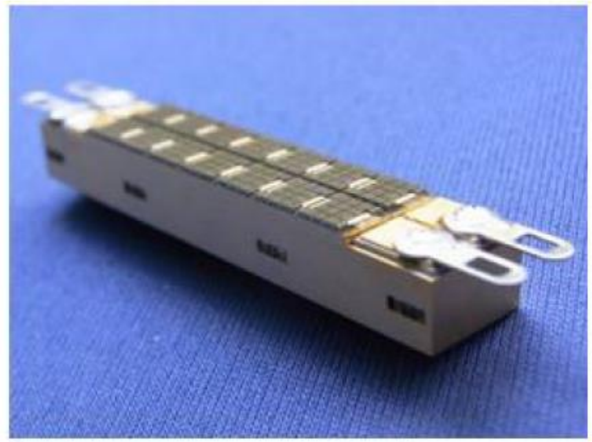
Figure 1 | Long-wavelength VCSELs. **a**, On a wafer. **b**, Individually. These have a lower power consumption than their edge-emitter counterparts at similar optical power level. In addition, their vertical-cavity design leads to better coupling to single-mode fibres (by a factor of 2–4) and enables on-wafer characterization, which greatly reduces manufacturing costs.

Scalability

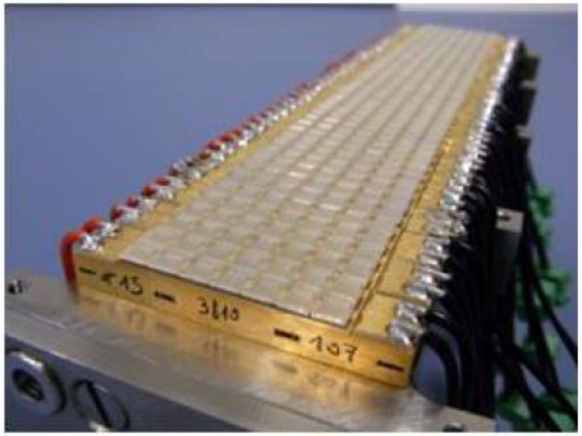
Building blocks of increasing power and size.



Chip with an array of thousands of VCSELs



Submodule with 12 x 14 chips on sub-mounts on a micro-channel cooler



System of 3.5 kW consisting of 24 sub-modules.

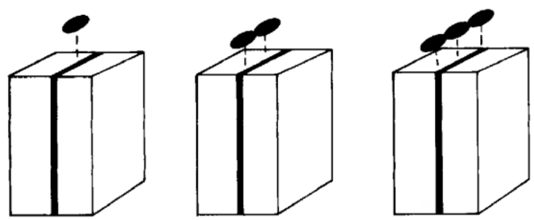
Source: VCSELs, R. Michalzik (2013)

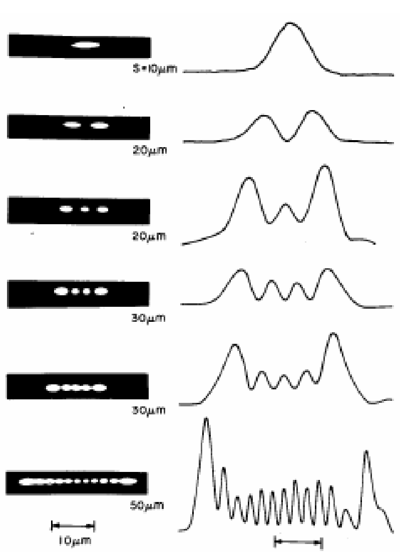
Lateral/transverse modes

Solutions of the Helmholz equation

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\mathbf{E}(x,y)+(k^2n^2(\mathbf{r})-\beta^2)\mathbf{E}(x,y)=0$$

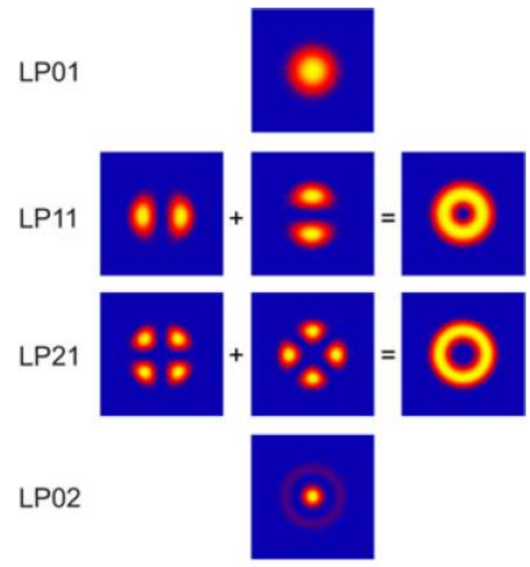
Edge-Emitting Lasers:





VCSELs:

- The circular profile allows **easy coupling to an optical fiber**.
- But single-transverse mode emission **limited to few mW**.



Fundamental mode operation can be achieved by matching the mode area to the active gain area.

Source: A. Larsson, J. Sel. Top. Quantum Electron. 2011

How does a VCSEL work?

The small cavity length requires highly-reflective DBRs, which are doped to facilitate the injection of electrons/holes

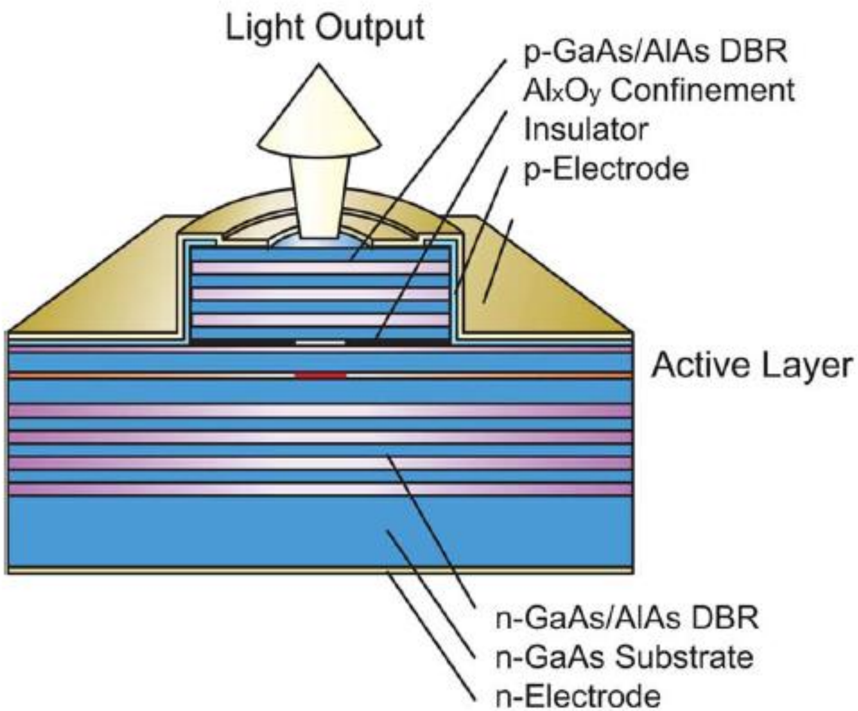
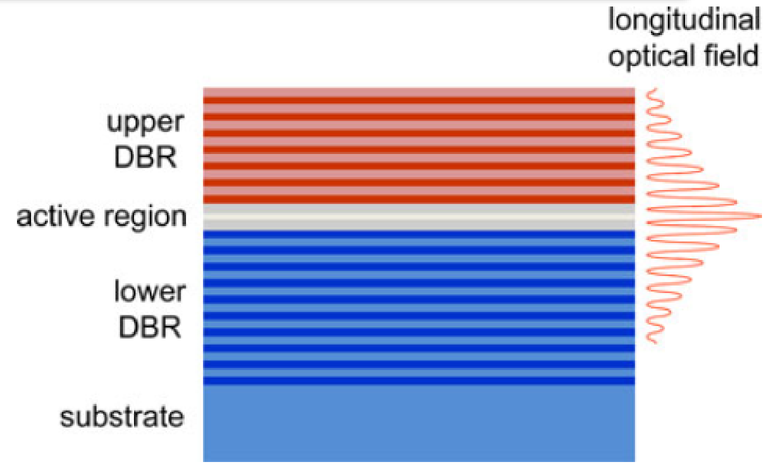


Fig. 6. Schematic structure of a typical VCSEL using GaAs/AlAs DBR and selective-oxidation technique. Various materials emitting wide wavelength ranges can be utilized as the active layer.



Blue indicates **n-type** material and **red** indicates **p-type**

The active region is composed of several QWs

Source: K. Iga, J. Lightwave Tech. 2008

Source: A. Larsson, J. Sel. Top. Quantum Electron. 2011

Problems with long wavelength VCSELs

- GaAs-based VCSELs were first demonstrated in the 80s; advances in manufacturing techniques allowed useful commercial devices by the late 1990s.
- GaAs VCSELs benefit from a large index difference between GaAs and AlAs that allows to fabricate high-reflective DBRs even with small numbers of layers.
- But long-wavelength VCSELs based on InP suffer from **small index contrast** of the InGaAsP or InGaAlAs mirror layers. Thus, **larger numbers of layer pairs** are required for good mirror reflectivity.
- Also a problem: larger layer thicknesses (due to the longer wavelength) leads to higher thermal resistance.

Comparison

Edge Emitter

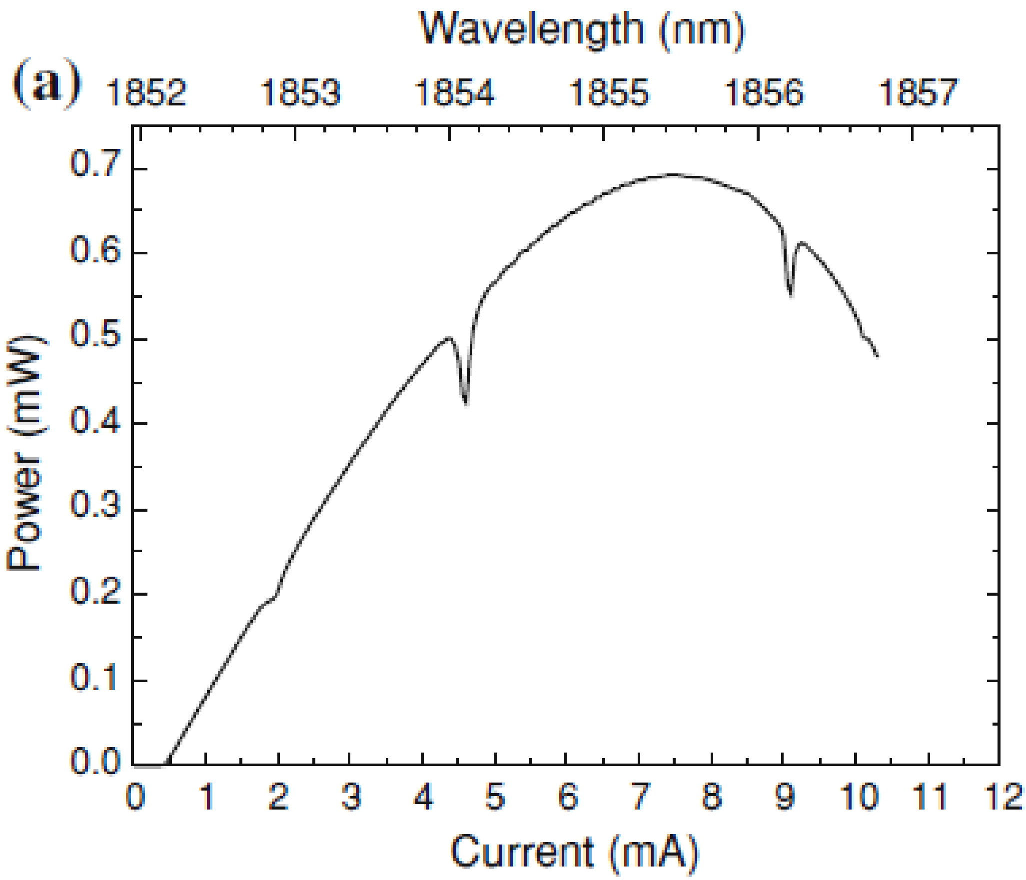
- Moderate threshold
- Larger active volume
  - Higher power
  - Efficiency to 60% commercial
    - to 71% R&D
- Small thin emitting area
  - Large divergence
  - Limits beam quality
  - Multiple emitters combine
- Long cavity (100s μm)
  - Multi longitudinal modes
  - DFB or DBR for singlemode
    - Single emitter

VCSEL

- Very low threshold
- Small active volume
  - Efficiency ~ 15% commercial
    - R&D to 56%
- Circular emitting area
  - 2-100 μm per VCSEL
  - Better beam quality
- Short cavity (~ 10 μm)
  - Single longitudinal mode in gain band
  - Stable wavelength
  - Narrow linewidth
  - Long coherence length possible
    - Single emitter

Source: J. Hecht, Laser focus world

VCSELs: typical electro-thermal current tuning rate of **0.3–0.6 nm/mA**



LI-curve of 1.85 µm VCSEL used for direct absorption measurements. The absorption dips of water vapor are clearly resolved.

~0.4 nm/C

Source: VCSELs, R. Michalzik (2013)

VCSEL technology is finding applications in consumer electronics and more.

Workers in photonics company Finisar's wafer testing area. Apple has committed to buy $390 million of VCSELs from the photonics company.

Source: SPIE news room, April 2018

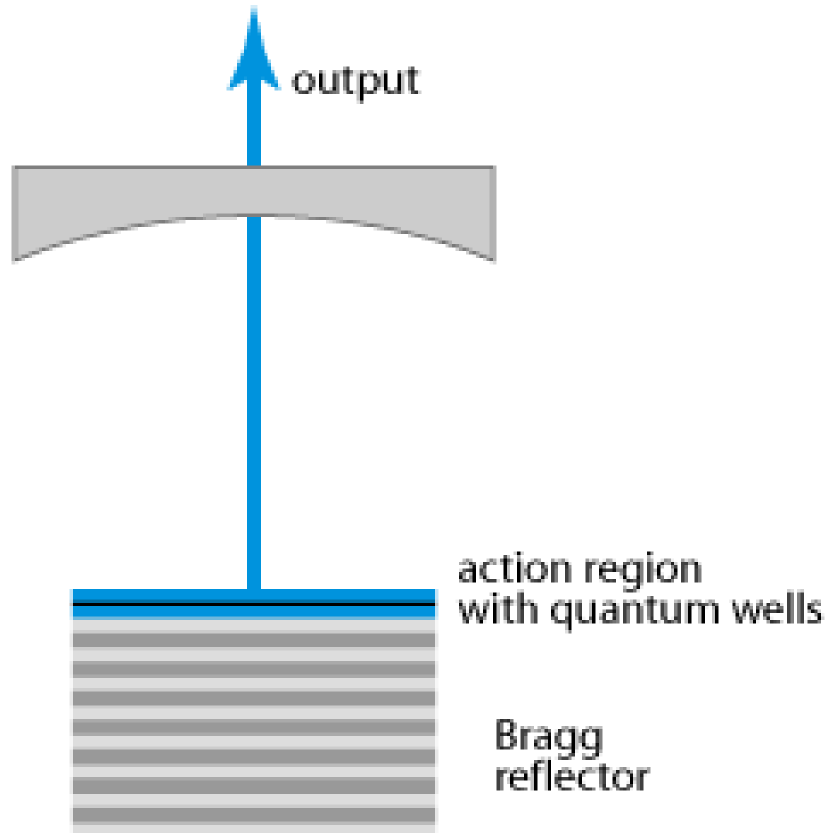
VCSELs in iPhone X

- To detect whether there is something in front of the iPhone X, it is believed that the phone uses a "*time-of-flight*" (TOF) sensor, powered by an LED-based infrared illuminator.
- TOF itself isn't new, having first been used in LG smartphones for the "laser autofocus" in 2014.
- This method illuminates an object repeatedly at a very fast rate, often using VCSELS, and measures the time taken for light to reflect or scatter back to a detector. It is especially useful for measuring distances and speeds.
- If the TOF sensor detects an object, it triggers the iPhone X's True Depth camera to take a picture.
- If that reveals a face, the phone activates its dot projector, shining a single infrared VCSEL through an optical system to create 30,000 spots while its infrared camera captures an image.
- It sends both regular and spottily illuminated IR face images to an application-processing unit (APU) that can recognize the owner and therefore unlock the phone.

Source: SPIE news room, April 2018

Vertical External-cavity Surface-emitting Lasers (VECSELs)

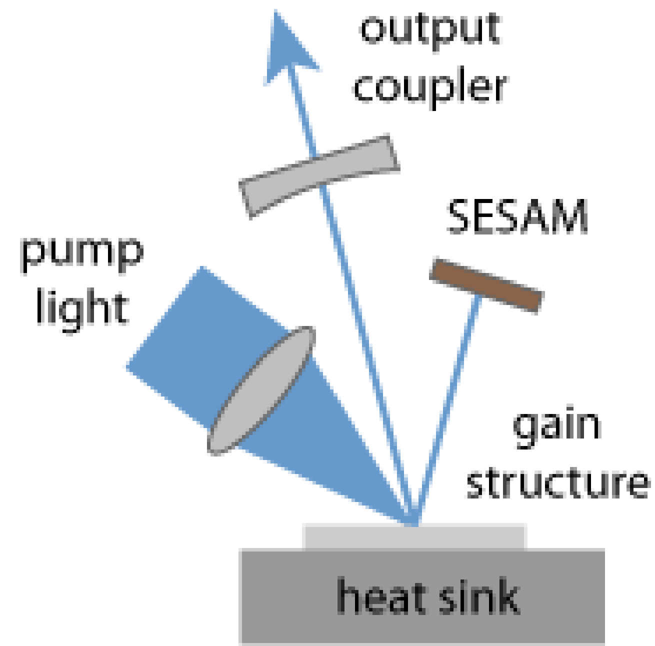
- GaAs & other III-Vs
- Bragg reflector on bottom of device
- External cavity (0.1 mm – few 10's cm)
- Output coupler
- Tunable (15-180 nm)
- Wavelengths: 670 nm to 2.2 μm
- Electric pumping limits the usable active area (and thus the output power), because it is challenging to pump large areas, uniformly.



Source: RP Photonics Encyclopedia

Optically pumped VECSEL

- The pump light is typically taken from a high-brightness broad-area laser diode or from a diode bar.
- Also known as *semiconductor disk lasers*.
- A semiconductor saturable absorber mirror (SESAM) produces *mode-locking* with few hundred MHz pulse repetition frequency.



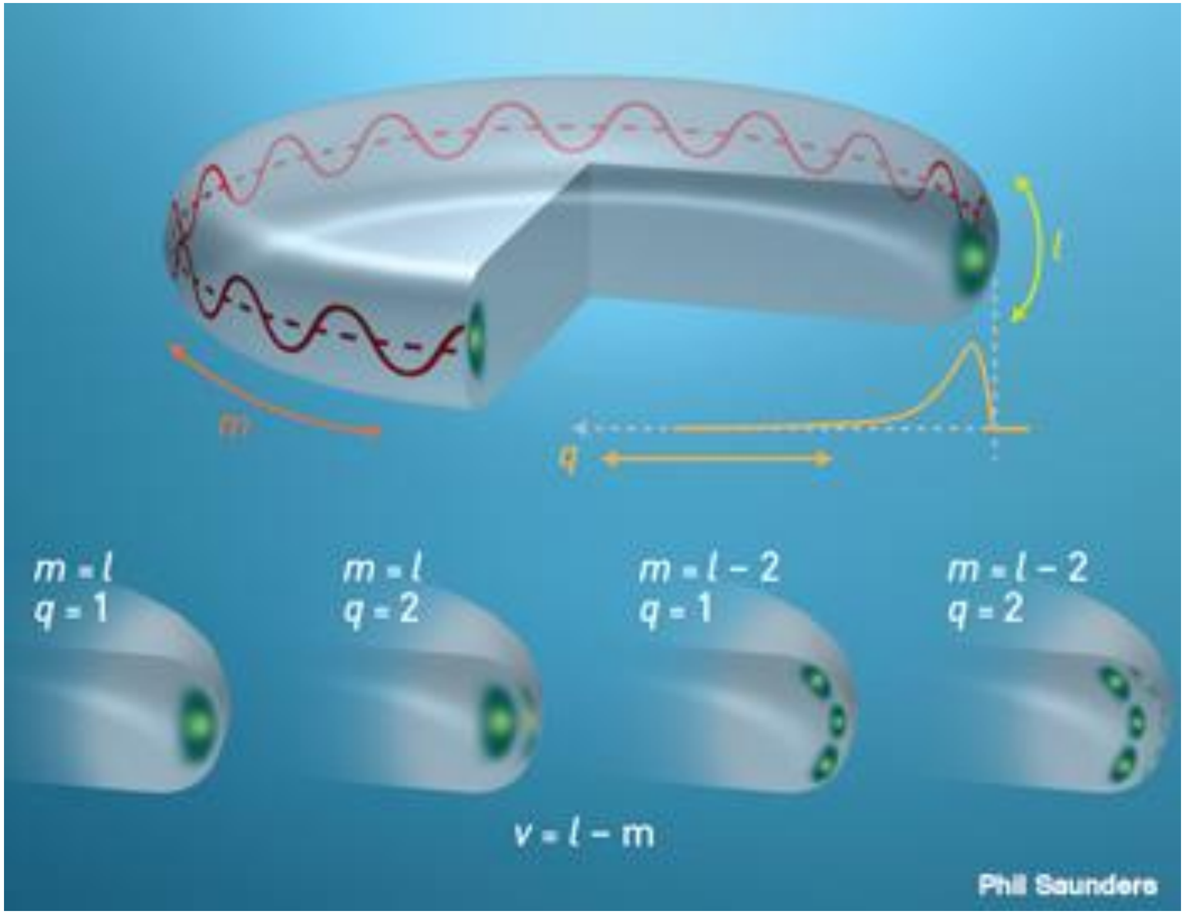
Further reading: *“Recent advances in ultrafast semiconductor disk lasers”*
Light: Science & Applications (2015), vol. 4, e310; doi: 10.1038/lsa.2015.83

Source: RP Photonics Encyclopedia

Ring cavity: whispering-gallery modes

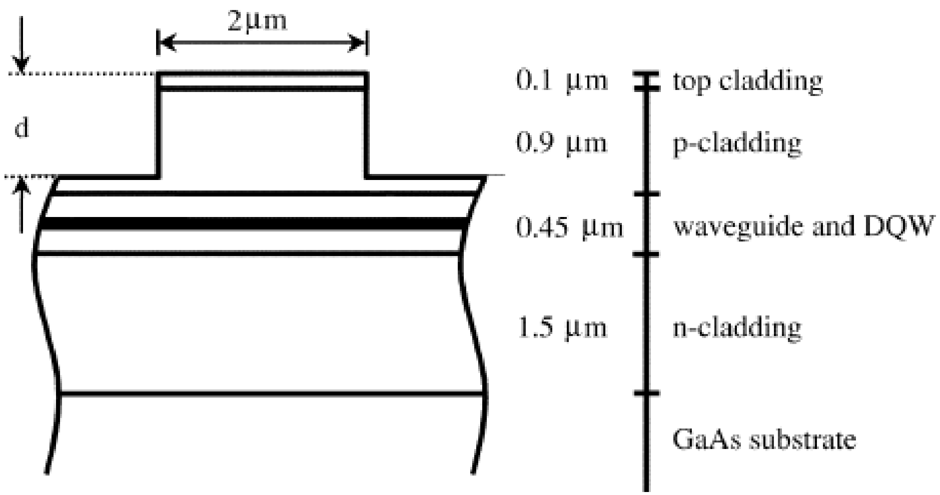
- Discovered by Raman in 1920 while visiting London Cathedral.

Whispering-gallery modes



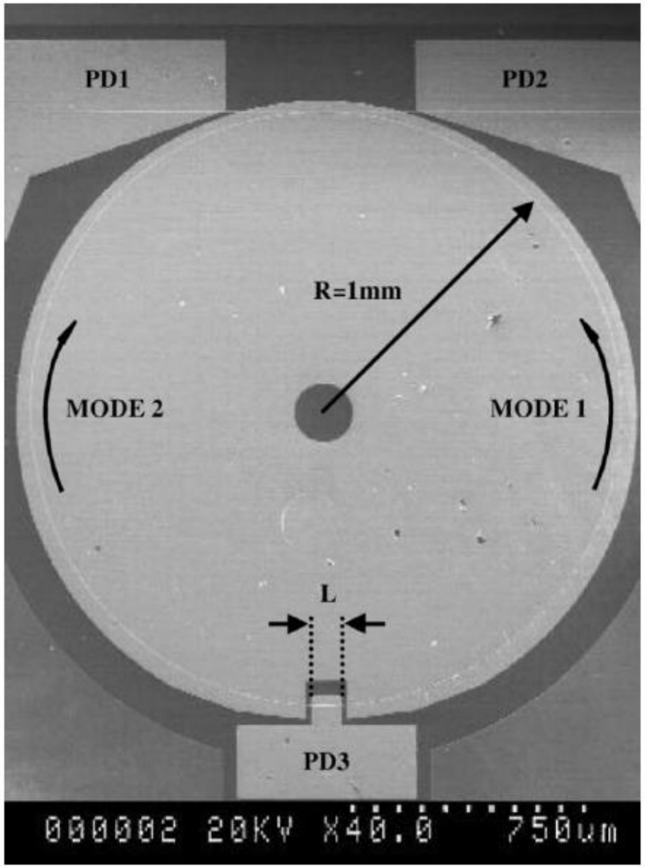
Source: OPN July 2013, May 2015

Microdisk ("ring") laser



(b)

Two "whispering-gallery" modes



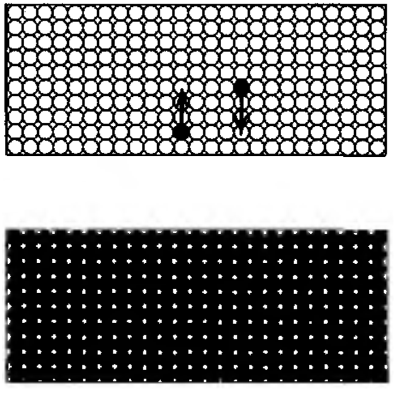
(a)

A thin disk of semiconductor material in which whispering-gallery modes circulate around the edge of the disk.

Source: Sorel et al, JQE 2003

A limit for the wavelength of semiconductor lasers

- In conventional semiconductor lasers, when electrons from the conduction band relax to the valence band, the energy is typically transferred to a photon.
- At longer wavelengths, depending on the band structure and temperature, this energy is often re-absorbed by another charge carrier and eventually transferred to heat.
- Thus, the emission wavelength of conventional, **inter-band** lasers is limited to about 3 μm.
- Solution: inter-subband transitions (quantized electronic energy levels within the conduction band).



Quantum Cascade Laser

Jerome Faist, Federico Capasso,* Deborah L. Sivco,
Carlo Sirtori, Albert L. Hutchinson, Alfred Y. Cho

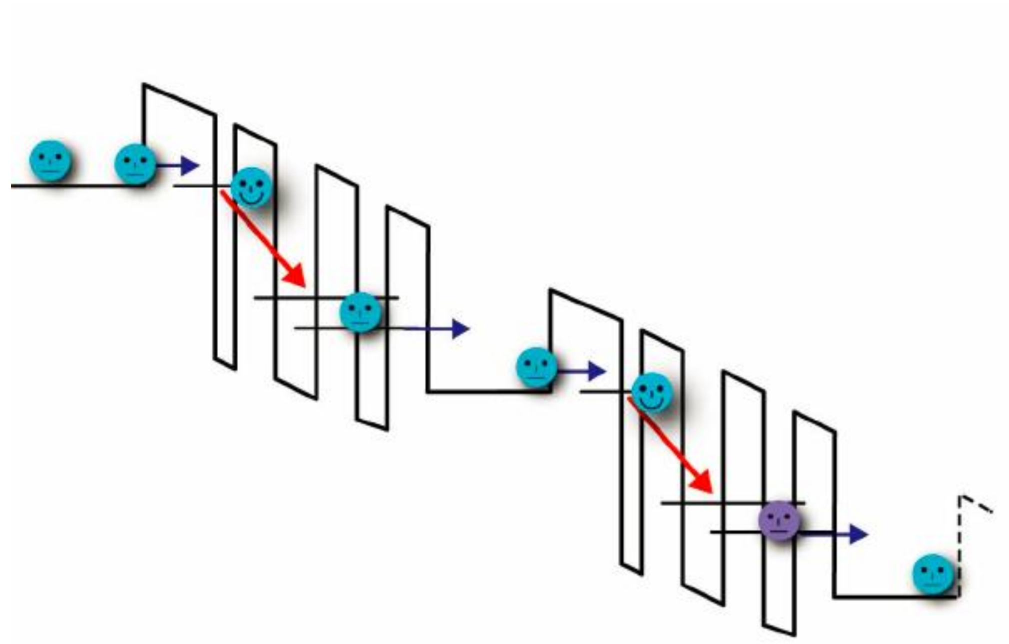
A semiconductor injection laser that differs in a fundamental way from diode lasers has been demonstrated. It is built out of quantum semiconductor structures that were grown by molecular beam epitaxy and designed by band structure engineering. Electrons streaming down a potential staircase sequentially emit photons at the steps. The steps consist of coupled quantum wells in which population inversion between discrete conduction band excited states is achieved by control of tunneling. A strong narrowing of the emission spectrum, above threshold, provides direct evidence of laser action at a wavelength of 4.2 micrometers with peak powers in excess of 8 milliwatts in pulsed operation. In quantum cascade lasers, the wavelength, entirely determined by quantum confinement, can be tailored from the mid-infrared to the submillimeter wave region in the same heterostructure material.

SCIENCE • VOL. 264 • 22 APRIL 1994

CW RT emission achieved in 2002

QCLs operating principle

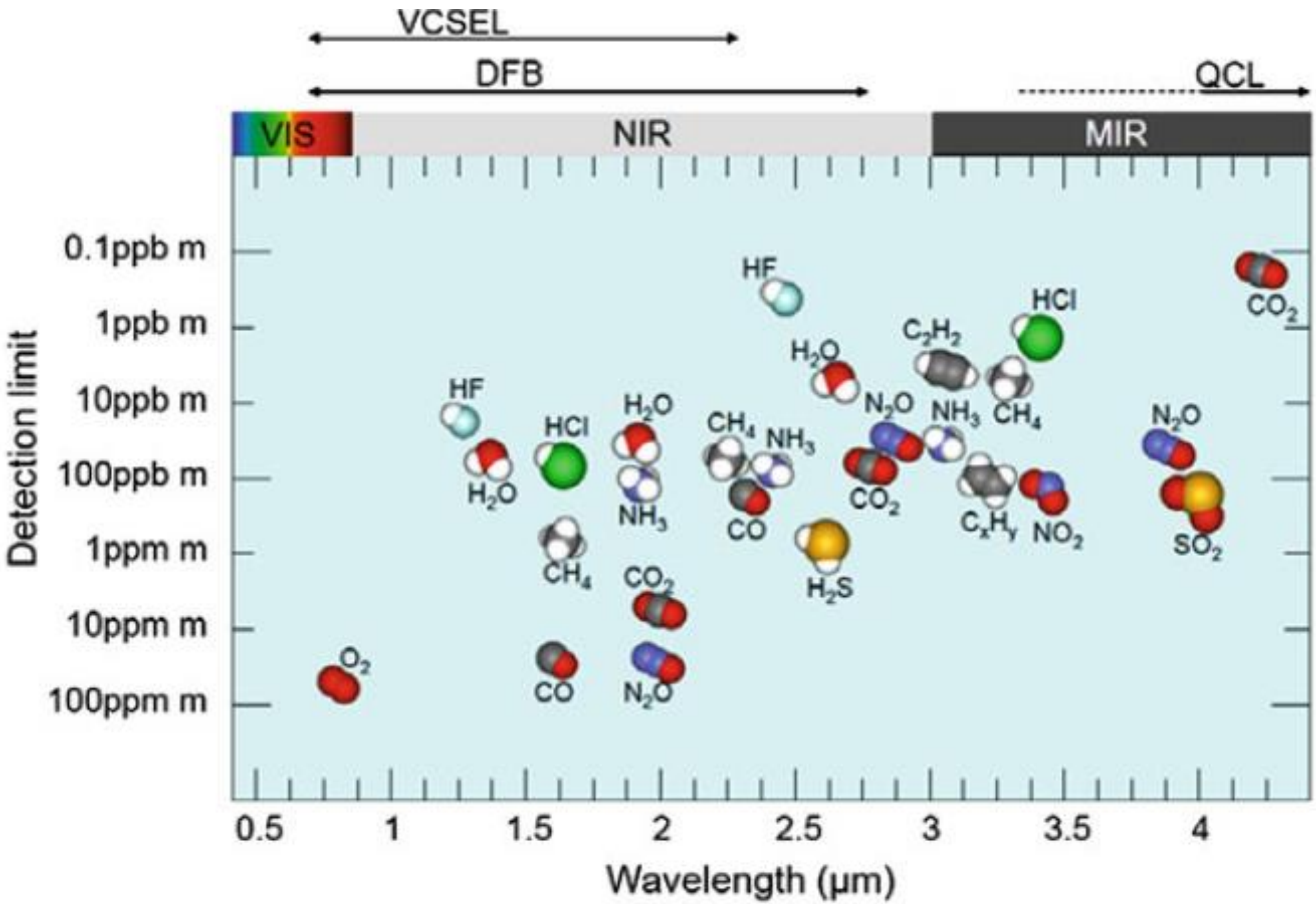
- No recombination!
- QCL: semiconductor laser but not diode laser.
- Electrons flow through series of quantum wells
- Emitting a photon each time.
- One electron generates many photons sequentially.



- Quantum well determines wavelength
- Wavelengths: mid- to far-infrared (~3 µm to THz)

Source: J. Faist, ETH Zürich

Sensing applications (single mode lasers)



Outline: semiconductor lasers

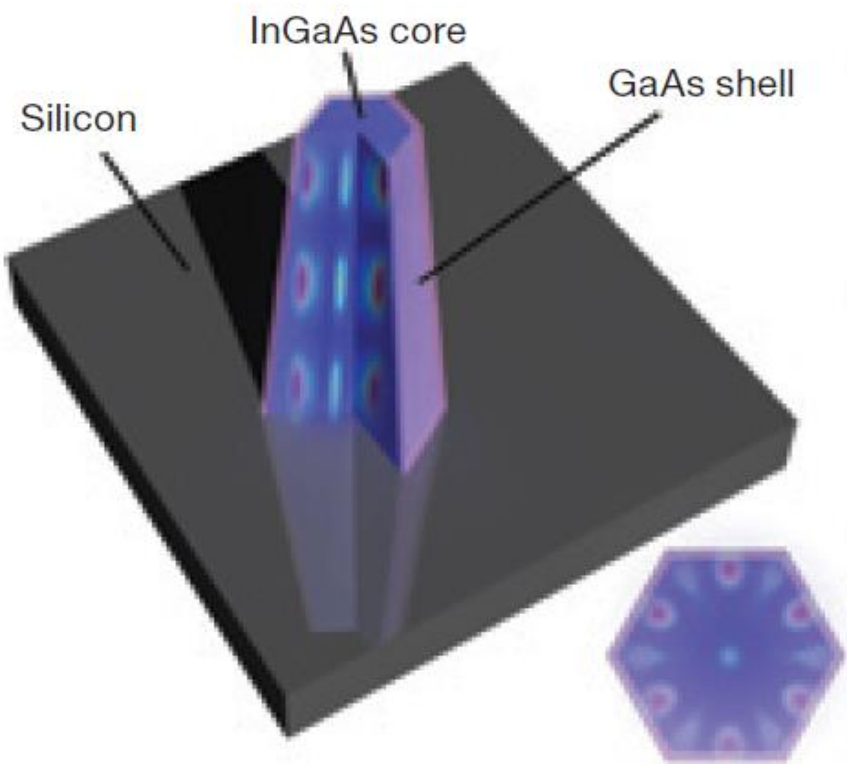
- Fabrication
- LI curve (efficiency, threshold)
- Characteristics (optical spectrum, thermal effects)
- Types of semiconductor lasers
- New materials and cavity designs

ARTICLES
PUBLISHED ONLINE: 6 FEBRUARY 2011 | DOI: 10.1038/NPHOTON.2010.315
nature photonics

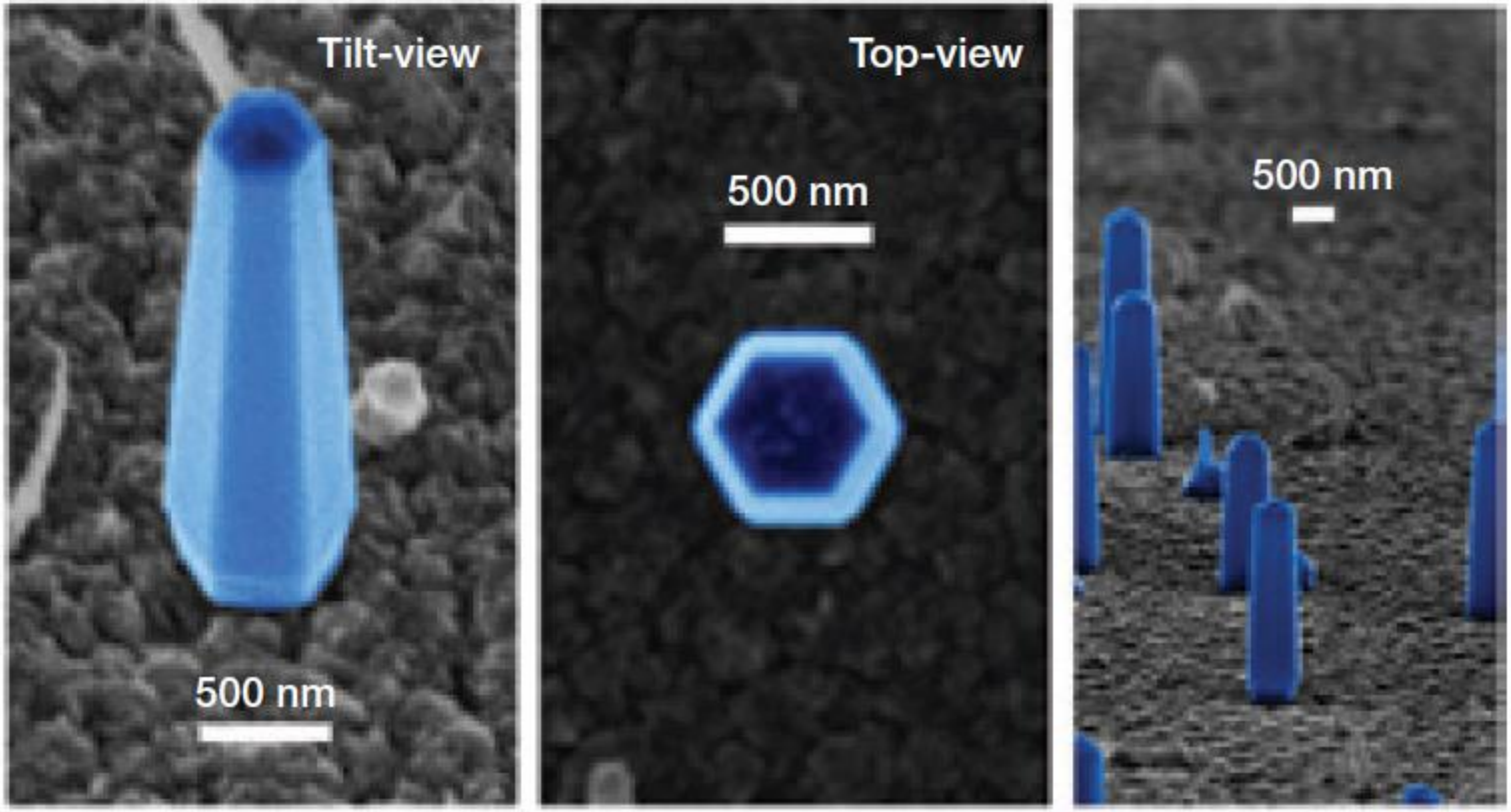
Nanolasers grown on silicon

Roger Chen, Thai-Truong D. Tran, Kar Wei Ng, Wai Son Ko, Linus C. Chuang, Forrest G. Sedgwick and Connie Chang-Hasnain*

- Like a whispering gallery mode, the light propagates around the edges of the pillars, but in a helix rather than a circle.
- Although light propagating downward is absorbed by the substrate, enough gain in the upward propagating allows lasing.
- The semiconductor cavity mode alone provides enough confinement (no need of metal cavity).
- **Sub-wavelength lasing**: the pillars are smaller on a side than the wavelength they emit.



Further reading: Optics and Photonics News, May 2011



Optically pumped by using a mode-locked Ti:sapphire laser

Nanolasers

- Have dimensions or modes sizes close to (or smaller than) the wavelength of emitted light.
- Developed thanks to innovative use of new materials and cavity designs.
  - dielectric lasers,
  - metallic and plasmonic lasers,
  - small bio-compatible or bio-derived lasers
- Applications
  - on-chip optical communications and data-processing (if lasers are compatible with silicon chips)
  - medical imaging and sensing (if biocompatible and implantable)

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Small lasers: historical development

- VCSELs (80’): a few λs
- Microdisk lasers & photonic crystal lasers (90’)
- They use differences in the refractive index of dielectrics to confine light in the cavity $\Rightarrow$ the overall size of the laser is larger than λ and the minimum possible optical mode size is determined by the diffraction limit.
- **Photonic crystal lasers**, demonstrated in 1998, use 2D/3D Bragg gratings to confine light to diffraction-limited volumes.
- **Nanowire lasers** (demonstrated in 2011): short (few-microns) Fabry–Pérot type resonators and very small transverse size.
- Metal-based resonant-cavity structures (demonstrated in 2010) enable overall size of lasers < λ, with optical mode dimensions less than the diffraction limit.

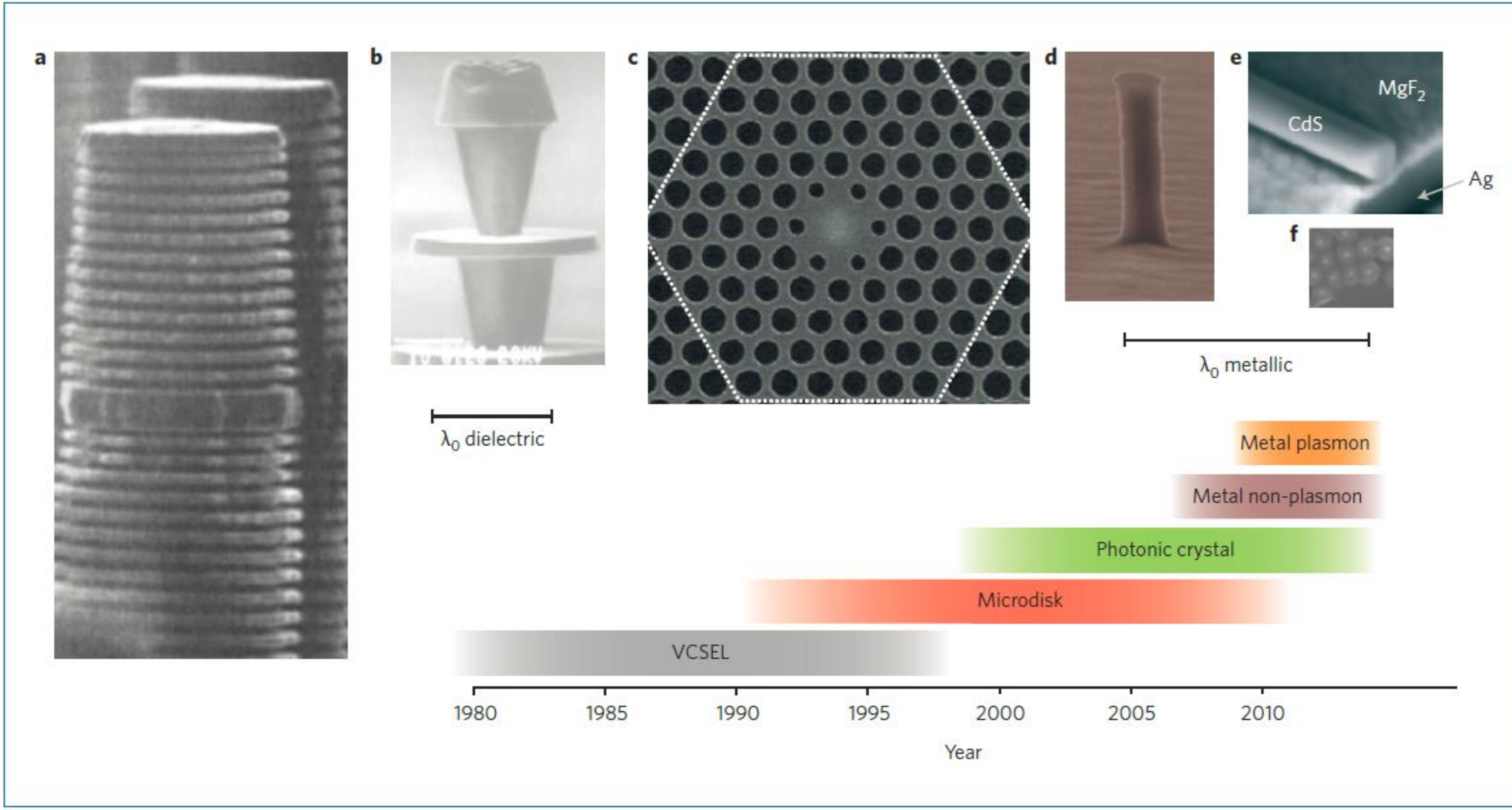


Figure 1 | Development timeline of small lasers, from first demonstration to electrical, continuous wave and room-temperature operation, and in some cases to commercial applications. It usually takes 10–20 years for a new laser concept to reach commercial applications. However, compared with conventional dielectric small lasers, recently developed metal-cavity lasers have seen very rapid development. Also shown is a size comparison of various types of small lasers. The electron microscopy pictures are scaled to the free-space emission wavelength λ_0 of each laser. **a**, VCSEL[94]. **b**, Microdisk laser[95]. **c**, Photonic crystal laser[96]. **d**, Metallic non-plasmon mode laser[17]. **e**, Metallic propagating plasmon mode laser[20]. **f**, Localized plasmon mode laser[19]. The free-space wavelength scale of the metal-cavity based lasers (**d–f**) is twice that of the dielectric lasers (**a–c**) to permit details to be seen. The metal-cavity lasers developed recently are typically smaller than λ_0 and dramatically smaller than corresponding dielectric-cavity lasers. See Supplementary Information Fig. S1 for details on the development milestones and their references. Figure reproduced with permission from: **a**, ref. 94, © 2012 Elsevier; **b**, ref. 95, © 1997 IEEE; **c**, ref. 96, © 2007 AIP; **d–f**, refs 17,19,20, Nature Publishing Group.

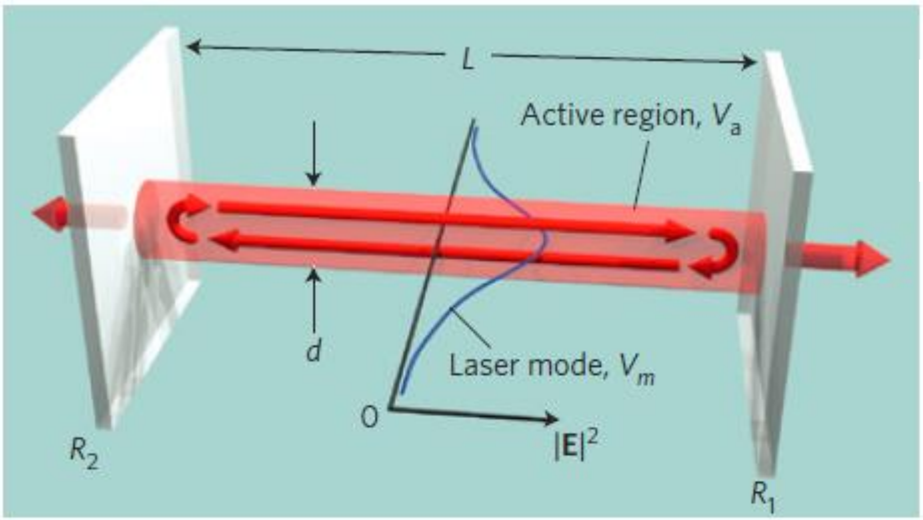
Exciton–polariton lasers

- No population inversion.
- Exciton–polariton condensation in microcavities represents a fundamentally different and potentially more efficient process for generating coherent light.
- Exitons-polaritons: quasiparticles **formed in resonators that provide strong coupling** between intracavity photons and the excitonic states of a gain medium inside the resonator.
- (Reminder: an exciton is a e/h pair held together by their Coulomb attraction).
- In the strong coupling regime, exciton–polaritons can form a condensate if their density is sufficiently high.
- **Photon leakage** from a resonator containing such a condensate yields **coherent light** that is nearly indistinguishable from conventional laser light.
- Polariton laser (proposed in 1996 and first demonstrated in 2003) exploits the coherent nature of exciton-polaritons condensates in semiconductors to achieve ultra-low threshold lasing.

Plasmonic lasers

- Employ metal cavities.
- Surface Plasmon: quantum electromechanical oscillator
- Surface plasmon–polariton (SPP) modes: electron oscillations are confined to the interface dielectric--conductor.
- First demonstrated with a FP cavity (Oulton *et al. Plasmon lasers at deep subwavelength scale*, *Nature* 2009).
- Also demonstrated with plasmonic photonic crystal cavities and whispering-gallery mode cavities.
- Also known as **SPASERs** = Surface Plasmon Amplification by Stimulated Emission of Radiation.
- The spaser is the smallest nanolaser: is $<<\lambda$ in all dimensions, but it has been demonstrated in samples that contain multiple small resonators.

Fundamental challenges involved in laser miniaturization



$$E_0\sqrt{R_1R_2}e^{(G_m-\alpha_i)L}e^{i4\pi nL/\lambda_0}=E_0$$

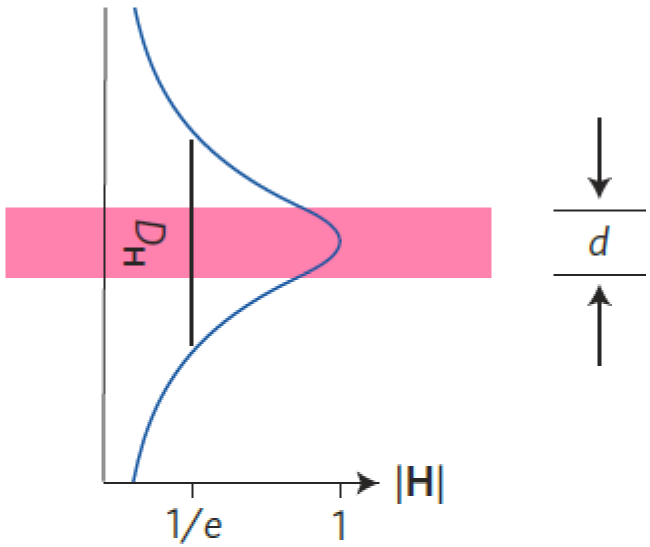
Phase condition $L=\dfrac{\lambda_0}{2n}m$

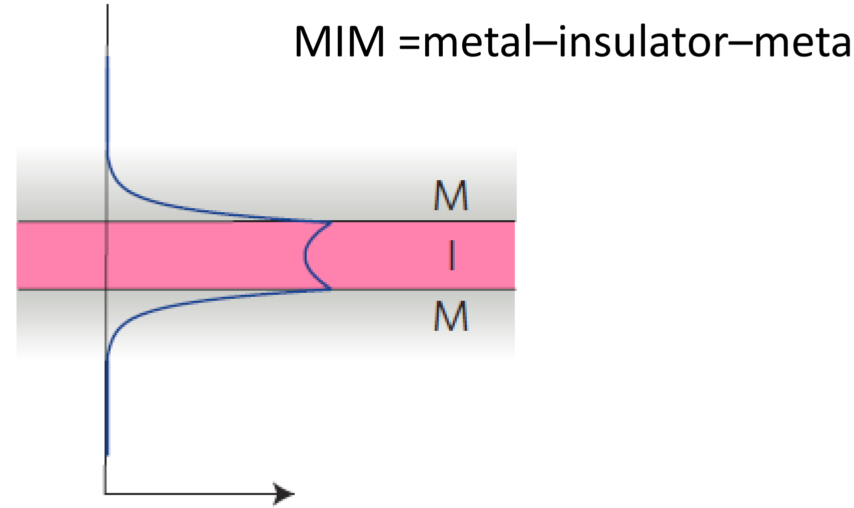
$\Rightarrow$ The shortest L is $\lambda_0/2$ (m = 1)
$\Rightarrow$ L reduced by increasing n

Amplitude condition $L=\dfrac{-\ln(R_1R_2)}{2(G_m-\alpha_i)}$ $\quad G_m=\Gamma G_a \quad \Gamma=\dfrac{\text{volume optical mode}}{\text{volume active region}}$

The gain limit is often the greatest constraint on *L*, as the cavity must be long enough to compensate for the mirror losses.

Limit in the transverse direction



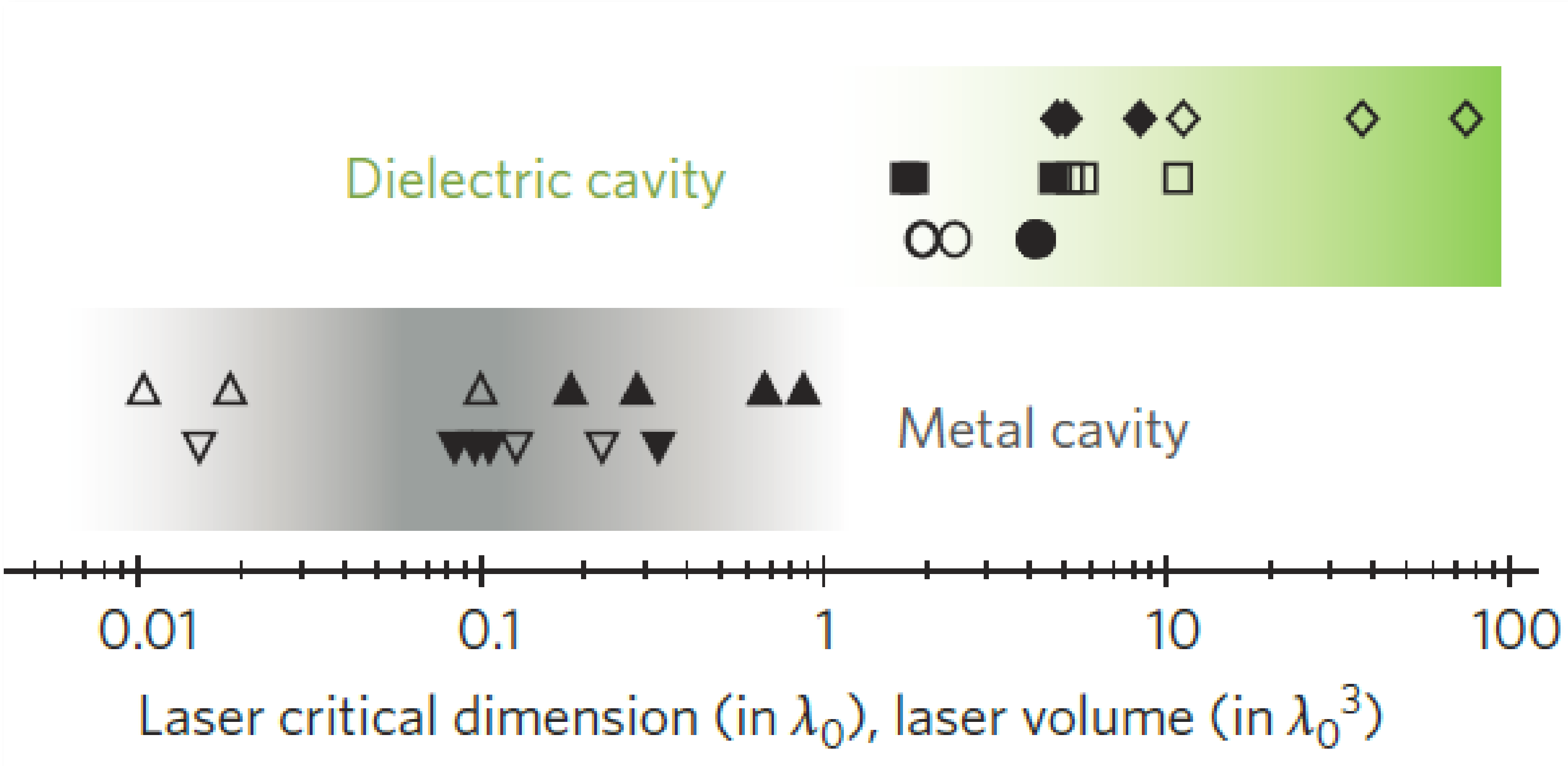


For lasers based on dielectric waveguides, reducing the thickness *d* of the waveguide leads to substantial broadening of the transverse field.

Metallic waveguides allow reduced transverse dimensions and a subwavelength localized transverse field, at the cost of increased loss due to absorption in the metal

Reducing a laser's transverse dimensions involves a trade-off between *confinement and losses.*

Comparison of small laser sizes



- Dielectric : VCSELs (♦); microdisk (■); photonic crystal (●).
- Metal: non-plasmon mode (▲); plasmon mode (▼).

- open symbols: volume
- filled symbols: dimension

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Comparison

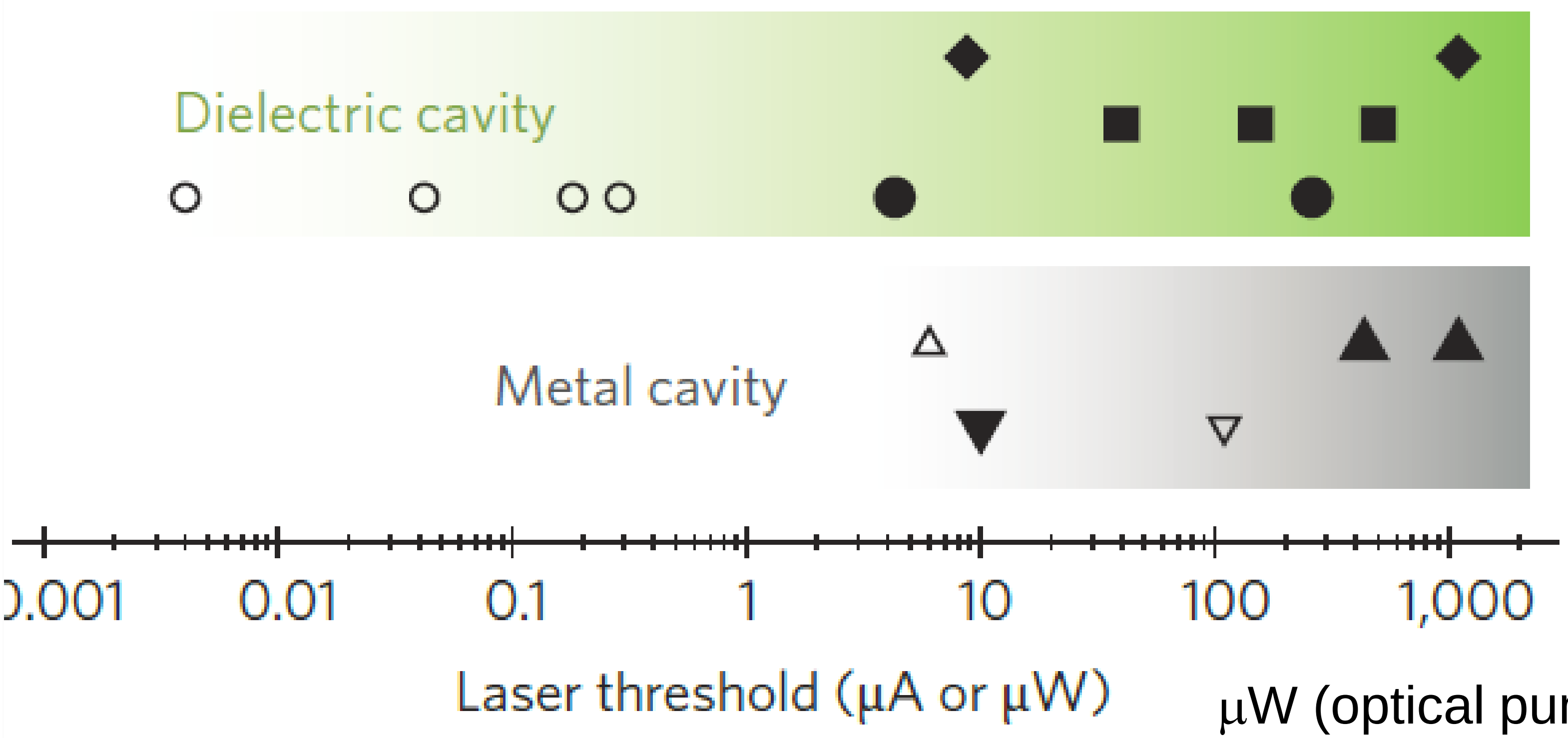
Dielectric cavity lasers

- employ cavities with long photon lifetimes to reduce demands on the gain medium.
- cavities with *Q* factors of >1,000
- dimensions and volumes greater than λ

Metal cavity laser

- shorter photon lifetimes, due to absorption in the metal.
- Increased confinement of the optical mode to the gain medium provides a design window in which lasing can occur.
- *Q* factors of <1,000
- Dimensions and volumes smaller than λ

Comparison of lasing thresholds

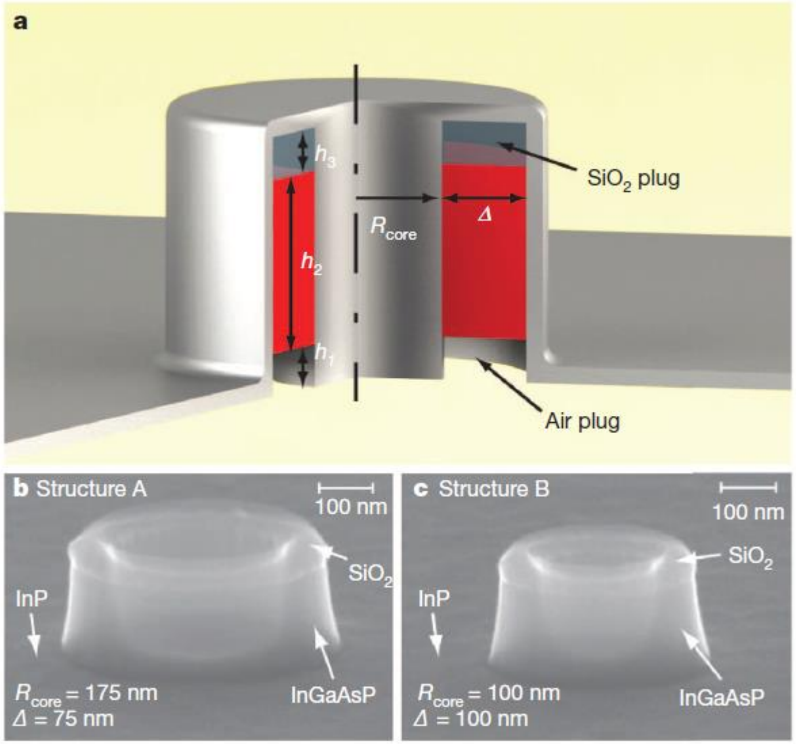


μW (optical pump) or
μA (electrical pump)

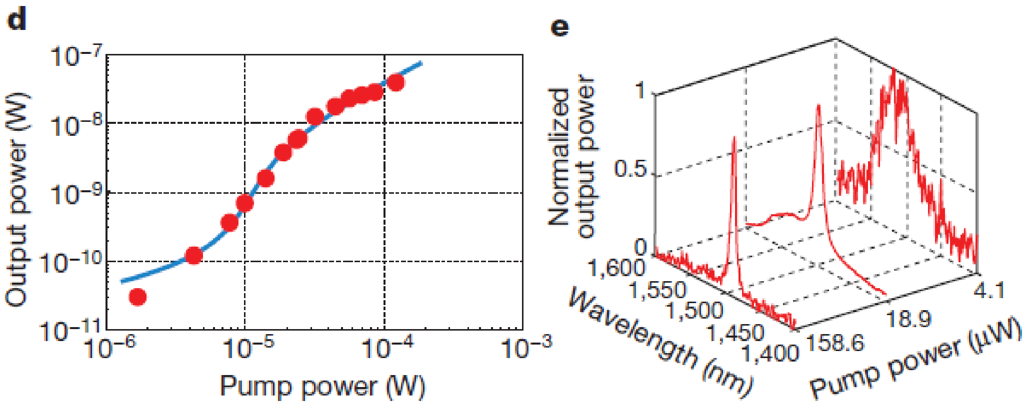
- Dielectric : VCSELs (♦); microdisk (■); photonic crystal (●).
- Metal: non-plasmon mode (▲); plasmon mode (▼).
  - Open symbols: cryogenic temp.
  - filled symbols: RT.

Thresholdless nanoscale coaxial laser

The smallest RT, continuous-wave telecom-frequency laser to date (2012).



Light-light curve: optical pumping with a 1,064nm laser pump beam



M. Khajavikhan et al, Nature 482, 204 (2012)

Active materials for small lasers

- Conventional semiconductors are the widely used because:
  - they allow direct electrical pumping and
  - they provide high optical gain. Specially QDs, however, there is the drawback of limited overlap of the optical mode with the small QDs.
- Main drawback of conventional semiconductors: tunability. Tunable lasers usually require complex fabrication processes.
- Alternative materials: organic dyes, organic semiconductors and colloidal quantum dot nanocrystals. They can be prepared as thin films (thicknesses <<1 μm) by solution-based processes.
- They gain spectrum can be tuned by targeted modifications of chemical structure, composition and characteristic dimension.

Alternative materials

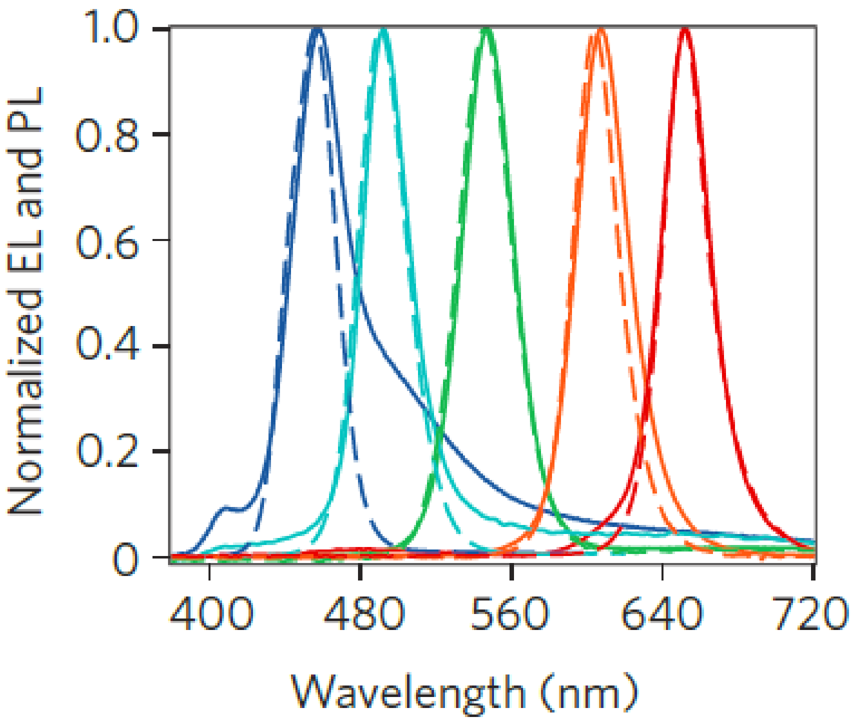
Organic semiconductors

- Hydrocarbon-based compounds with strong optical transitions and electronic semiconducting properties.
- Drawback: low carrier mobility.

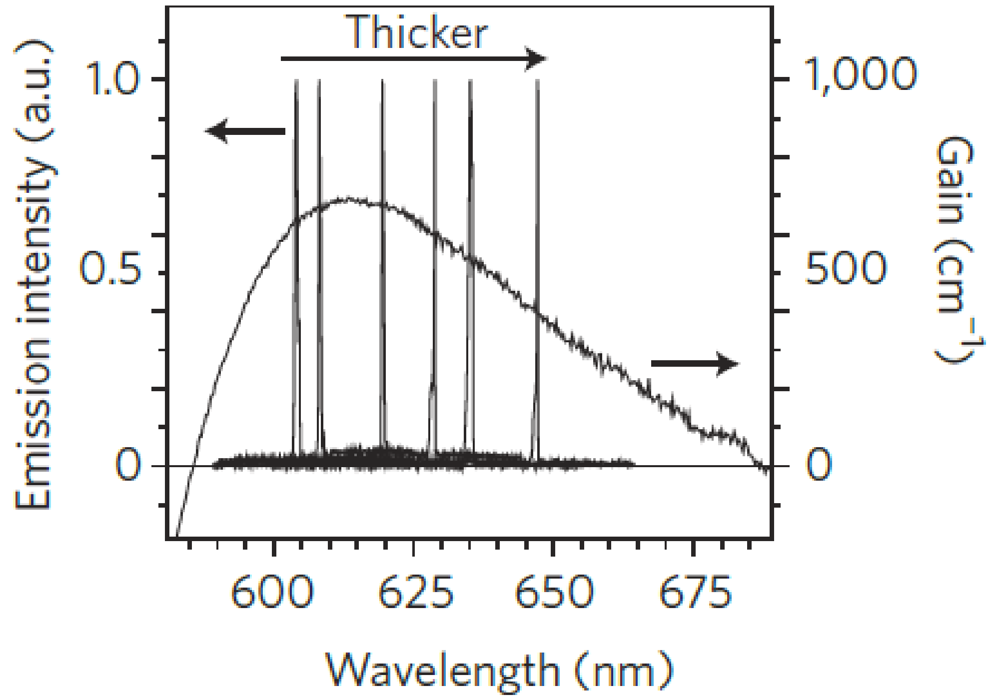
Fluidic lasers

- Organic dye solutions have been used in macroscopic, wavelength-tunable dye-lasers at visible and near-infrared.
- Microfluidics has enabled the application of such solutions in small lasers (fluidic lasers).
- In fluidic lasers the refractive index and gain spectrum are tuned by the solvent or dye passed through the device.

Tunability



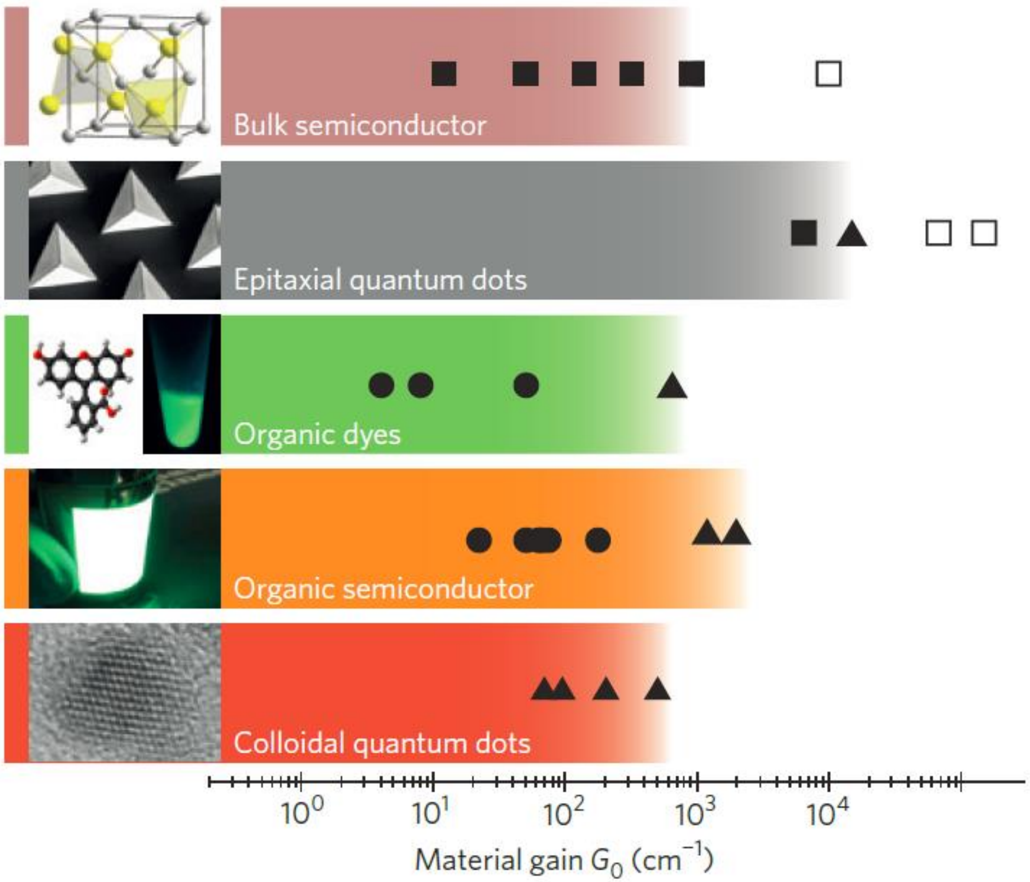
Photoluminescence (PL) and electroluminescence (EL) spectra from five different types of colloidal quantum dots, spanning the entire visible spectrum.



Emission wavelength of organic-semiconductor-based distributed feedback lasers, tuned by adjusting the thickness of the gain layer.

Optical gain materials used in small lasers

broad emission and gain spectra that can be tuned by chemical modification or size variation



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Squares: electrical pumping;

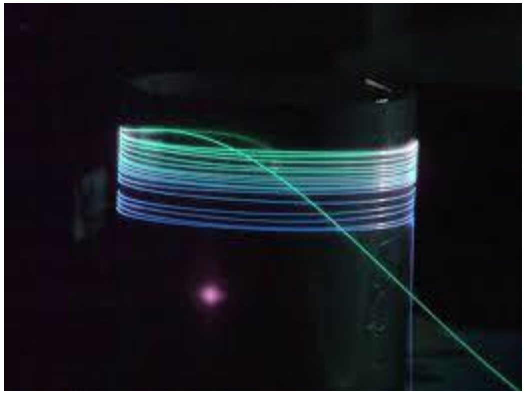
Circles: amplified spontaneous emission (ASE) with nanosecond optical pumping;

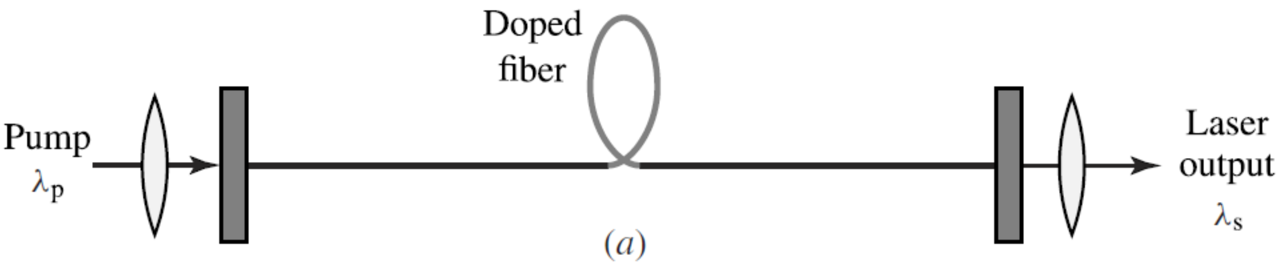
Triangles: ASE subpicosecond optical excitation;

open symbols: gain achieved at cryogenic temperatures

Fiber lasers: in the other extreme of cavity sizes

- Gain medium: optical fiber, doped with rare-earth ions (Erbium-doped is one of the most common).
- Why erbium?
- Erbium atoms have very useful energy levels: there is one that can absorb 980 nm photons, and decays to a meta-stable state at 1550nm.



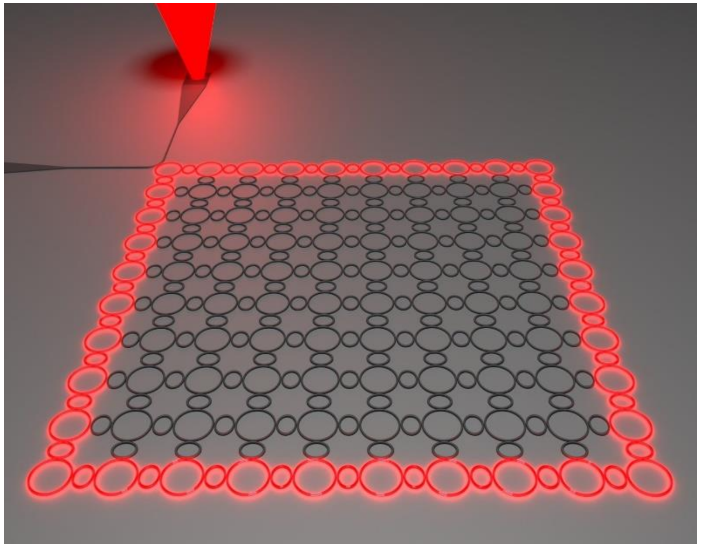


Km long cavity, millions of longitudinal modes

Main advantage: portability. The delivery of the beam does not require any sensitive optics.

Recent development: Topological insulator laser

- Applying topological physics to lasing creates more highly efficient and robust lasers
- Two papers published in Science (Feb. 2018).
- Topological protection: a property that provides stability to a system even in the presence of defects.
- Harari *et al.* outline a theoretical proposal that carries such ideas over to geometrically designed laser cavities. The lasing mode is confined to the topological edge state of the cavity structure.
- Bandres *et al.* implemented those ideas to fabricate a topological insulator laser with an array of ring resonators.
- The results demonstrate a powerful platform for developing new laser systems.



- Topological insulators: special materials that are insulators in their interior but conduct a "super-current" on their surface that is not affected by defects, sharp corners or disorder; it continues unidirectionally without being scattered.

- Scientists built a special array of micro ring resonators whose lasing mode exhibits topologically-protected transport – light propagates in one direction along the edges of the laser array, immune to defects and disorder and unaffected by the shape of the edges.

Importantly

- The fabricated array **used standard semiconductor materials**, without the need for magnetic fields or exotic magneto-optic materials; hence it can be integrated in semiconductor devices.

- Not only are topological insulator lasers theoretically possible and experimentally feasible, but also, integrating these properties **create more efficient lasers.**

Read more at:
https://www.osa-opn.org/home/newsroom/2018/february/a_topological-insulator_laser/

By the way: Nobel Price in Physics 2016

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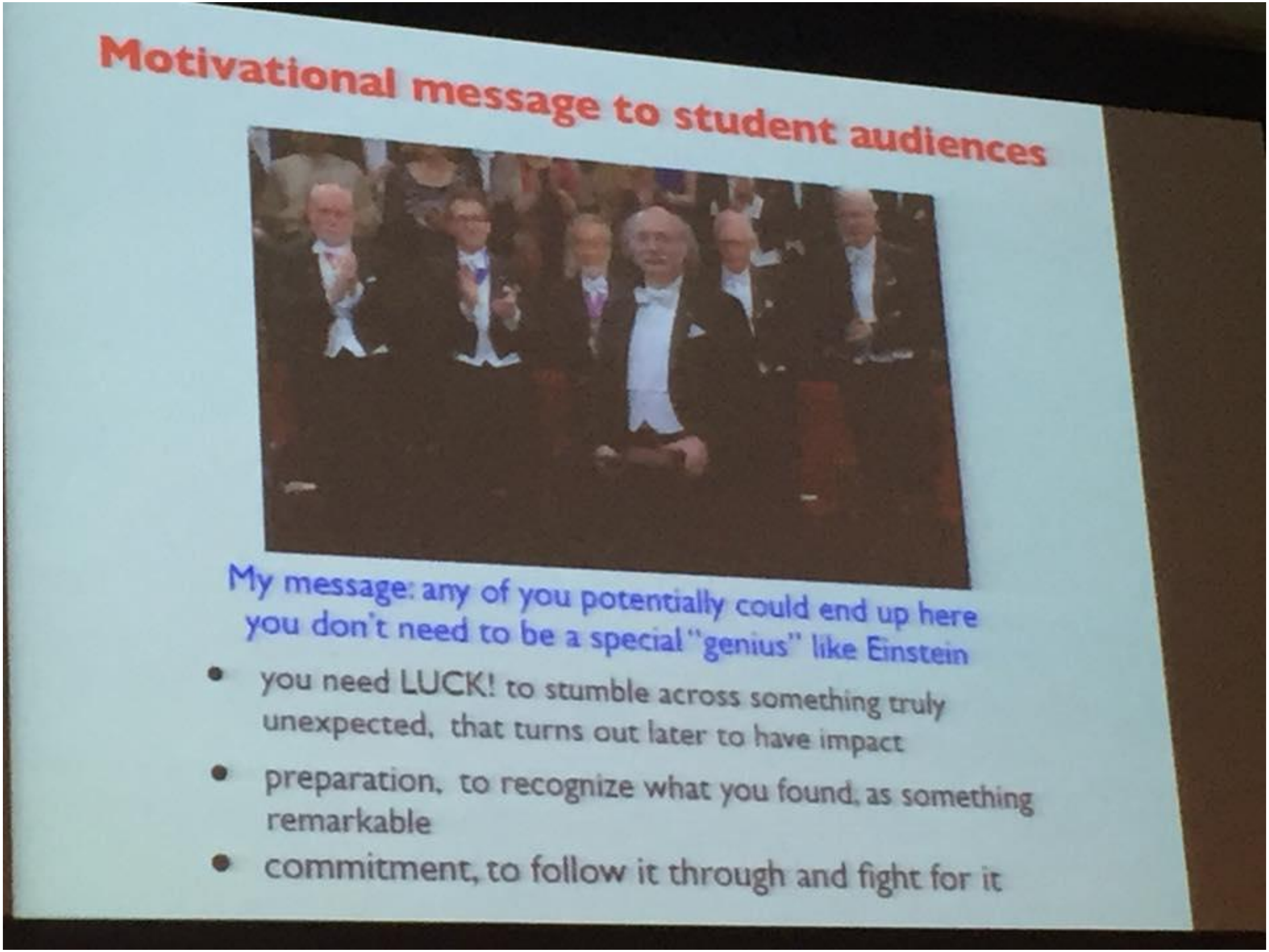
David J. Thouless
Prize share: 1/2

F. Duncan M. Haldane
Prize share: 1/4

J. Michael Kosterlitz
Prize share: 1/4

"for theoretical discoveries of topological phase transitions and topological phases of matter."



Source: Prof. F. Duncan M. Haldane presentation at the fall meeting of the Brazilian Physics Society, 2018

Summarizing, the design goals of the new generation of semiconductor light sources are:

- To optimize carrier injection properties
- To optimize optical confinement
- To minimize optical loss and heating
- To obtain maximum gain at a given injection power
- To obtain high-quality spatial profile and spectral purity
- To cover a wide range of wavelengths

TF test

- In EELs the Fabry-Perot cavity is formed by the cleaved facets of the semiconductor material.
- EELs and VCSELs have active regions of comparable sizes.
- Bragg-Grating lasers (DFBs and DBRs) emit a multimode spectrum.
- The goal of diode laser design is to improve the confinement of photons and carriers, which allows lowering the threshold current.
- The threshold of diode lasers and amplifiers is at transparency, when the rate of stimulated emission is equal to absorption.
- Thermal heating is responsible for the saturation of the LI curve and the shift of the emission wavelength with increasing current.
- Bulk lasers are as efficient as QW lasers.
- With respect conventional lasers, nano lasers require active materials with larger material gain because mirror losses must be compensated over a shorter length.

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