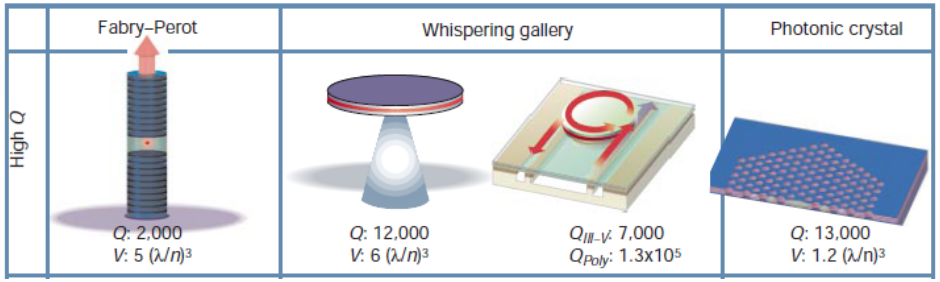
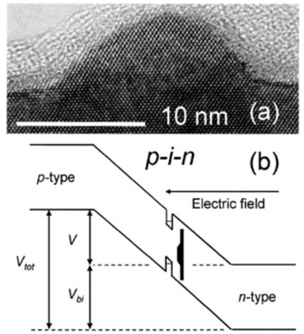
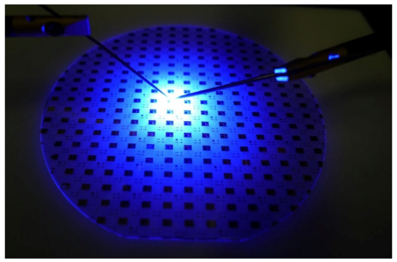
Physics of photonic semiconductor devices

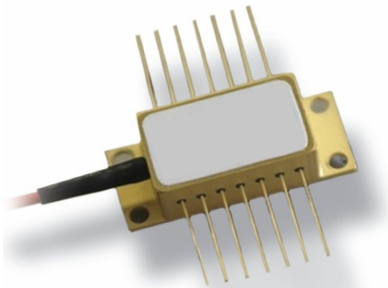
Lectures: Dr. Raphaël Butté (MER/senior scientist)
Teaching assistant: Alexandros Bampis (PhD student)

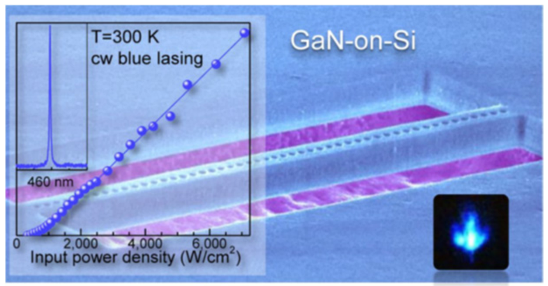
Physics - Master, spring semester 2025











Who are we?

Raphaël Butté (Lectures)

- PhD in Physics, Univ. Lyon, France, 2000
- Postdoctoral research associate, Univ. Sheffield, UK, 2000-2003
- Senior scientist at LASPE (https://laspe.epfl.ch/), EPFL, 2004-

Research interests: III-V semiconductors (III-N, III-As), quantum nanostructures and single photon emitters, optoelectronic properties, nanophotonics incl. microcavities, photonic crystals and photonic integrated circuits (microring resonators, waveguides, etc.), LEDs and laser diodes

Contact: CH A3 465, raphael.butte@epfl.ch

Alexandros Bampis (Exercises)

- Degree in Quantum Engineering from CentraleSupélec, France, & MSc. in Engineering Physics from KTH, Sweden, 2023
- PhD student at LASPE, EPFL, 2023-

Research interests: III-N semiconductors, single photon emitters, optical characterization (microphotoluminescence, photon statistics)

Contact: CH A3 495, alexandros.bampis@epfl.ch

Philosophy of the lectures and the exercises

- **Lectures** essentially **based on the textbook "Optoelectronics"** by E. Rosencher and B. Vinter (Cambridge University Press, Cambridge, 2002), paperback book available at the central library (+ eBook).

- A **more advanced description** about **laser diodes** as a whole is available **in the textbook "Diode Lasers and Photonic Integrated Circuits, 2nd edition"** by L. A. Coldren, S. W. Corzine, and M. L. Mašanović (John Wiley & Sons, Inc., Hoboken, 2012) $\Rightarrow$ *reference book worldwide for the physics of laser diodes!*

- **Master lectures** are a **transition between propaedeutic years and the world of work**: no dedicated lecture notes as teaching support, relevant and complementary information to be accessed mostly in textbooks and sometimes in articles

Philosophy of the lectures and the exercises

- **Exercises supervised by Alexandros Bampis. Each week the exercises** will be introduced during the exercise session and then will have to be **solved at home**. **Exercises are compulsory and will count for the final mark (1 pt out of 6).** Electronic (scanned) version to be uploaded on Moodle each week. The corrections will be made available ~two weeks after the series.

Aim: focus on important/essential physical concepts described in the lectures, **handle mathematical tools**, work on concrete examples, **develop your ability to handle back-of-the-envelope calculations**. Especially useful in view of the final exam.

- **Written examination: 3 hours, full access to the content of the lectures + related notes and the exercises** (no book, etc.). **Format of the exam: ~2/3 on problem solving and ~1/3 on analysis of figures** (implying the detailed description of physical phenomena).

Downloading lectures + exercises

- **PHYS-434 (spring semester)**

https://moodle.epfl.ch/course/view.php?id=14200

Progressive access to the pdf files of past lectures + exercises + live-streamed lectures from past years

- **PHYS-433 (fall semester)**

https://moodle.epfl.ch/course/view.php?id=14314

Full access to the existing pdf files of past lectures + exercises + live-streamed lectures from past years

- Use of **Ed Discussion** via Moodle as a forum tool to manage questions related to the lectures and the exercises. **But live questions during the lectures or following appointment in my office are strongly preferred!**

Recommended textbooks

- **E. Rosencher and B. Vinter, "*Optoelectronics*" (Cambridge University Press, Cambridge, 2002)**
  https://www.cambridge.org/core/books/optoelectronics/86B6621671230A798D5BFBE24266EE3F

- **L. A. Coldren and S. W. Corzine, "*Diode Lasers and Photonic Integrated Circuits*" (Wiley, New York, 1995)**
  https://onlinelibrary.wiley.com/doi/book/10.1002/9781118148167

- S. M. Sze "*Physics of semiconductor devices*" (John Wiley & Sons, New York, 1981), http://onlinelibrary.wiley.com/book/10.1002/0470068329

- G. Bastard, "*Wave mechanics applied to semiconductor heterostructures*" (Les éditions de physique, Les Ulis, 1992), *no ebook available*

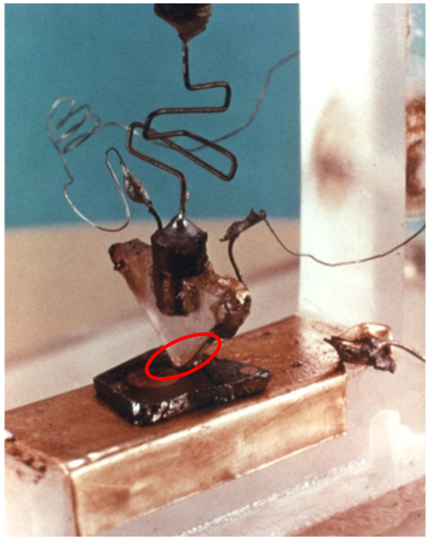
Content of the spring semester

1. **Semiconductor nanostructures**
   a. Growth and fabrication
   b. Electronic properties of quantum wells (QWs) and superlattices
   c. Electronic properties of triangular QWs and quantum dots (QDs)
   d. QDs used as single photon emitters (SPEs) and alternative solid-state SPEs

2. **Dielectric cavities**
   a. Microcavities, photonic crystals and microdisks
   b. High Q/V cavities and Purcell effect

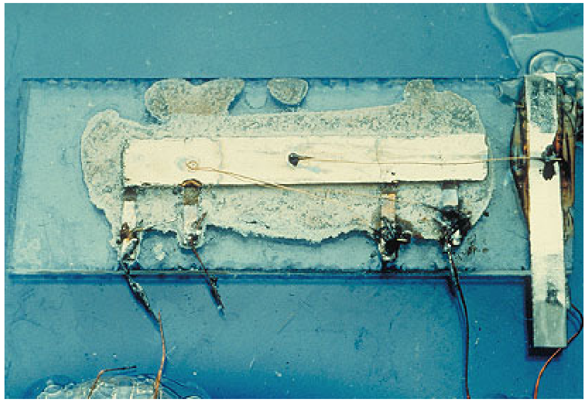
3. **Optoelectronic devices**
   a. Basic properties of LEDs
   b. Efficiency and fabrication of LEDs. Case of white LEDs
   c. Blue and green LEDs: what is governing the internal quantum efficiency?
   d. LDs: electrical injection, stimulated emission, material gain (bulk and QWs)
   e. LDs: laser oscillation, output power, LDs with QWs, beam profile, optical gain measurements
   f. LDs: mode spacing, DFB lasers, Schawlow-Townes linewidth, relaxation oscillations, VCSELs
   g. High-β nanolasers, quantum cascade lasers

Semiconductors: a brief overview

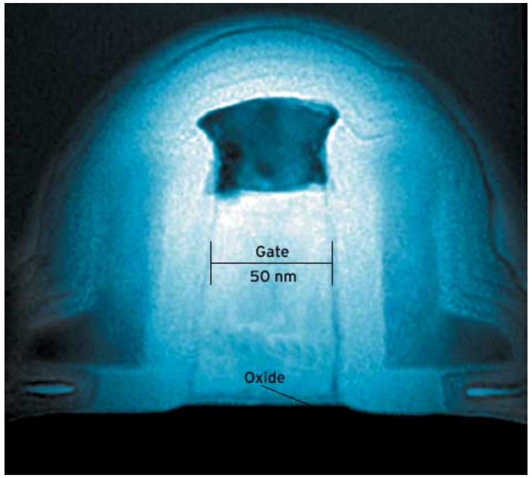


1947
1st transistor (Ge-based)
Bell Labs

1960's → **Silicon based electronics**



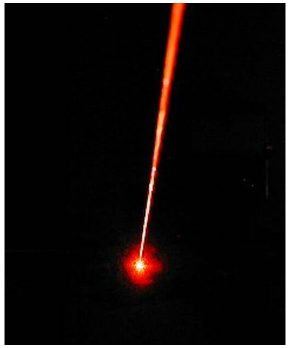
1958
1st integrated circuit
Texas Instruments



2007
Toward ultimate MOSFETs

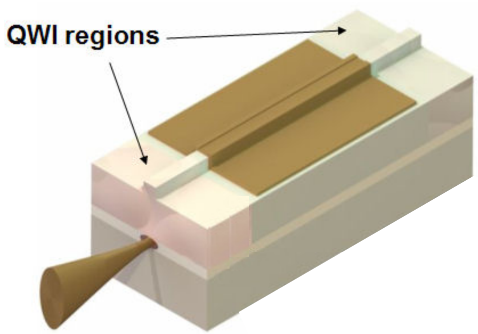
BUT not suited for light emission

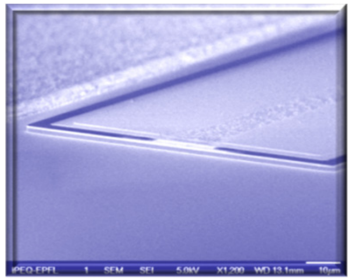
Semiconductors: a brief overview

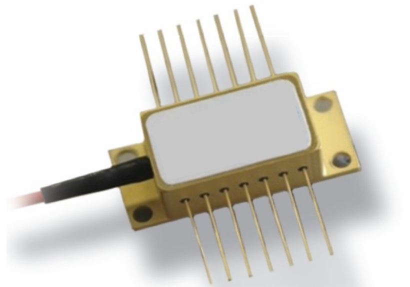


1970
1^{st} laser diode @300K
λ~ 780 nm
J_{thr}~ 4.3 kA/cm^2
Ioffe, Russia

1980's → **GaAs based optoelectronics**







2000

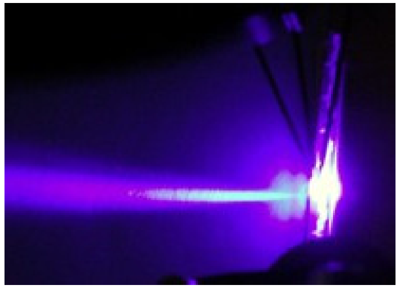
CD, DVD, Telecom

BUT light emission limited to the **Red** and **IR**

Semiconductors: a brief overview

1993

1990's → **GaN short-wavelength optoelectronics**



UV, blue, and green LEDs
High density DVD, color displays

2003

→ **White LEDs**

Semiconductors: a brief overview

Centenial light bulb

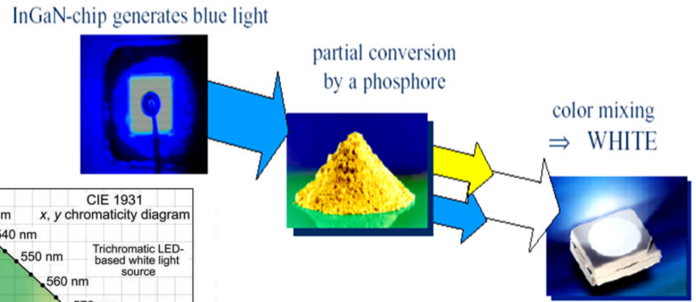
LED light bulb

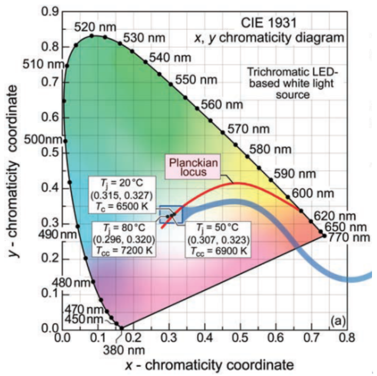
GaN is the building block of solid-state lighting (2nd most important semiconductor family after silicon, #1 for optoelectronics)

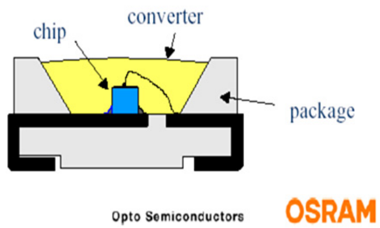
Luminous efficiency

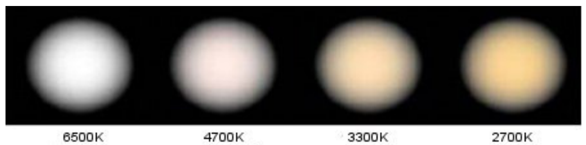
200 lm/W

Incandescent ×12
Fluorescent ×2.5







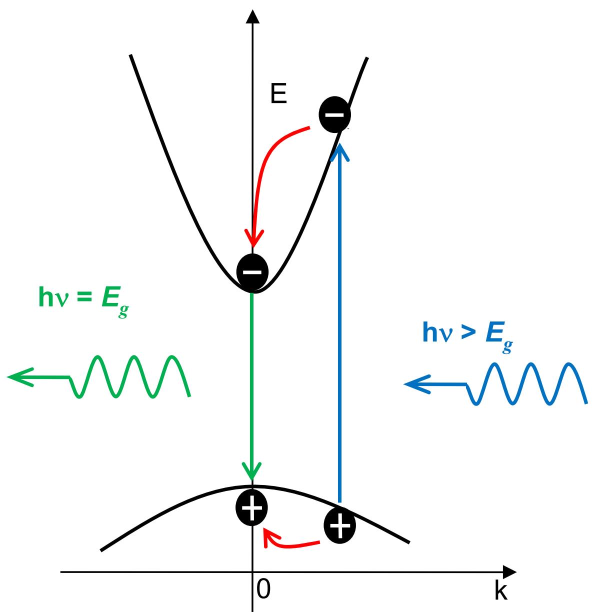


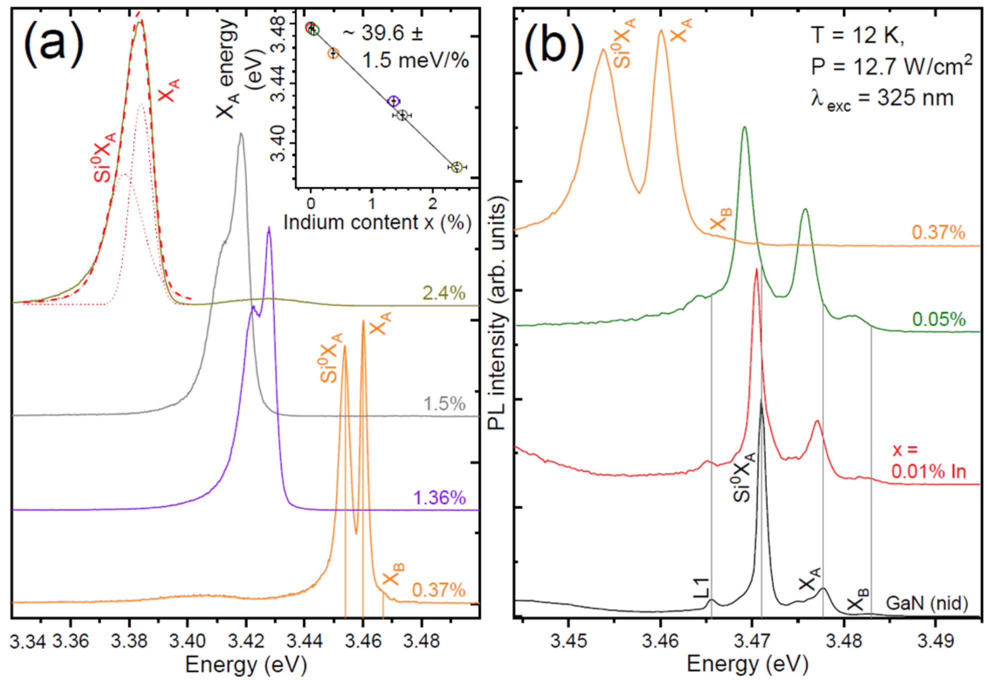
Optoelectronic devices

⇨ Both electrons and photons are involved

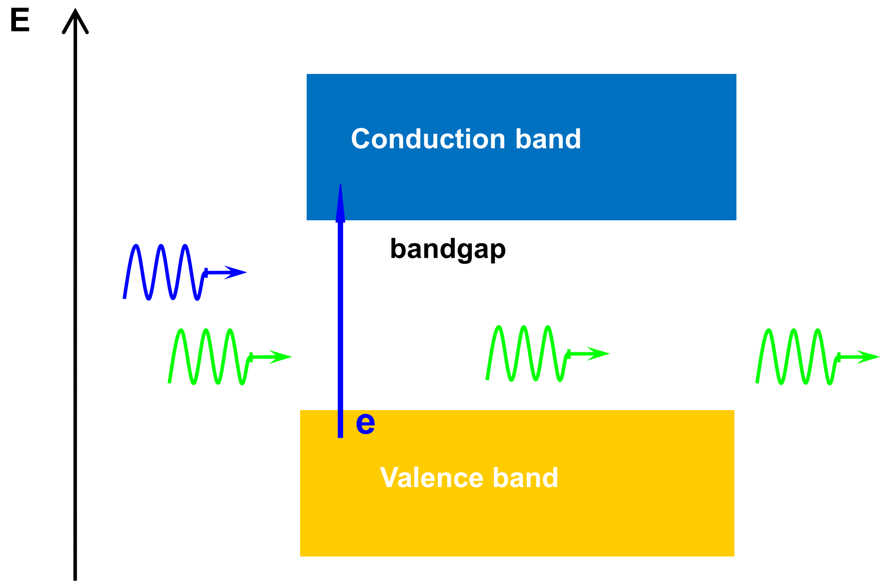
- **Emission**
  - ⇨ To convert electrons into photons
- **Detection**
  - ⇨ To convert photons into electrons
- **Modulation**
  - ⇨ To modulate an optical signal via an electrical excitation
- **Amplification**
  - ⇨ To amplify an optical signal via an electrical excitation

Luminescence – light emission

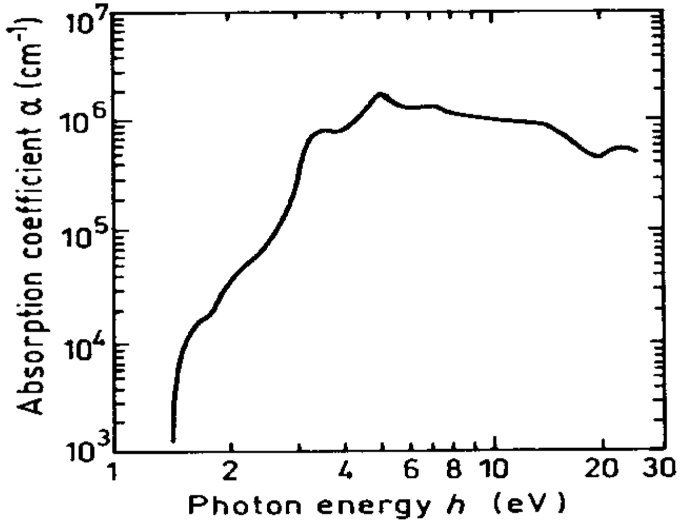




Absorption – light detection



Case of GaAs



Optoelectronic devices and their applications

- **Emitters**
  - Light-emitting diodes
  - Superluminescent diodes
  - Laser diodes (bipolar devices)
  - Quantum cascade lasers (unipolar devices)
- **Detectors**
  - Avalanche photodiodes
  - Quantum well infrared photodetectors (QWIPs)
  - Solar cells
  - CCDs
- **Modulators**
  - High frequency modulation (GHz)
- **Amplifiers**
  - Telecom applications

- **Light emitting diodes**
  - Lighting
  - Displays
  - Water purification
- **Laser diodes**
  - CD-ROM, DVD
  - Printing
  - Projection
  - Communication
- **Solar cells**
  - Power plant
  - Mobile power supply
- **Detectors**
  - Infrared
  - Ultraviolet

Pocket projectors – head up displays

Laser beamer

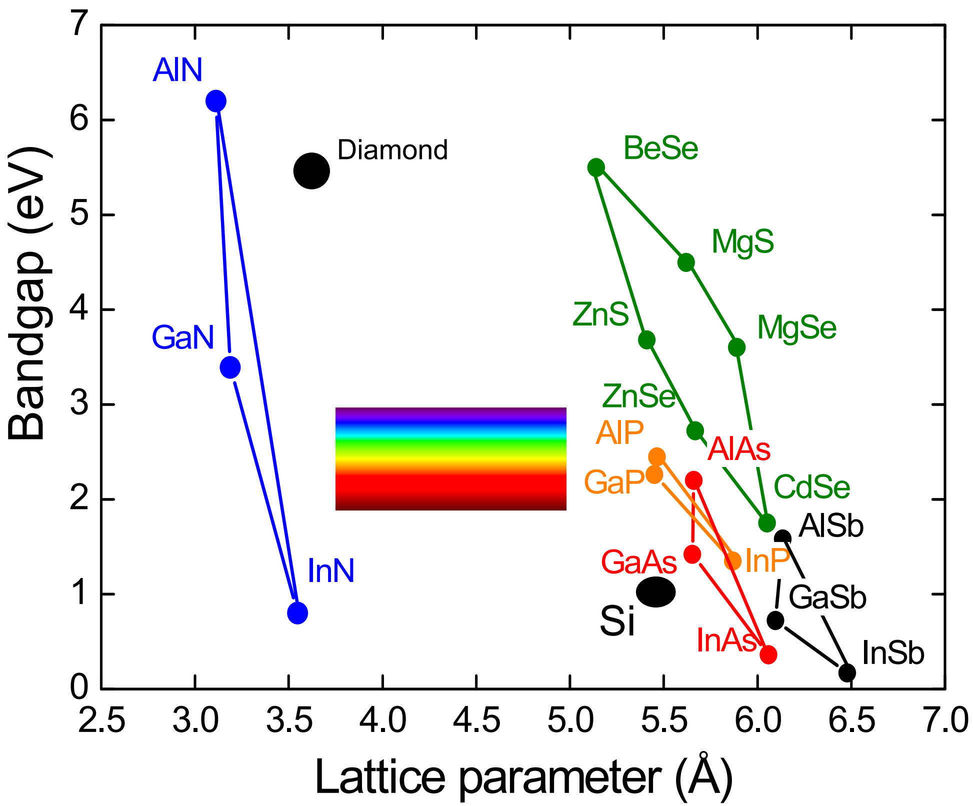
Laser Dream Theater at the Aichi Expo

Impact of high-definition screen of more than 6M pixels – 50 meters wide and 10 meters high (equivalent to 2005-inch TV)

Semiconductors – basic properties

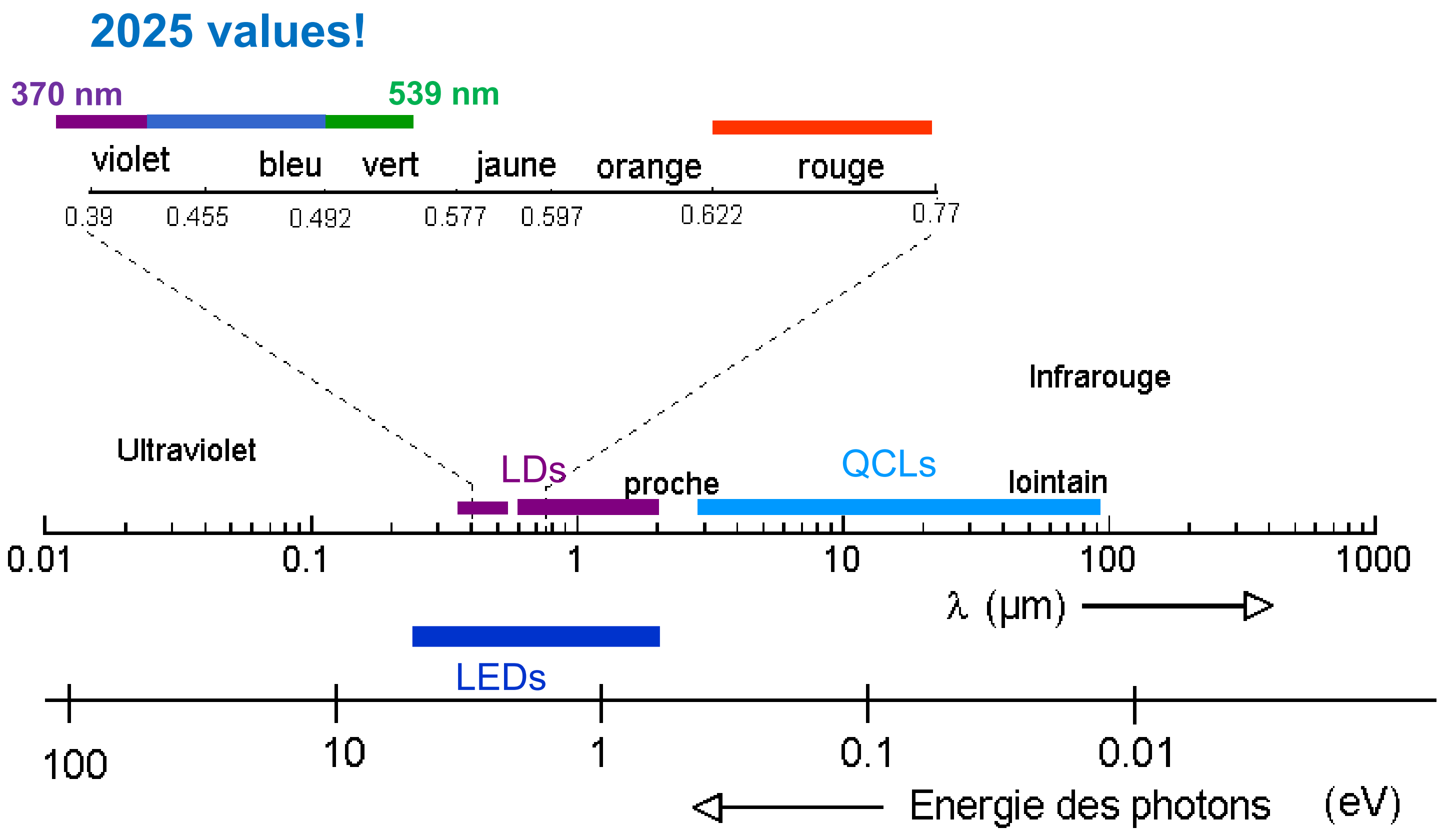
- Band structure (gap, effective mass)
- Conductivity control (*p*-*n* junction)
- Fabrication
  - Integration ⇒ higher yield: cost and performance
  - Quantized heterostructures, bandgap engineering

Semiconductors for optoelectronics



II	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te

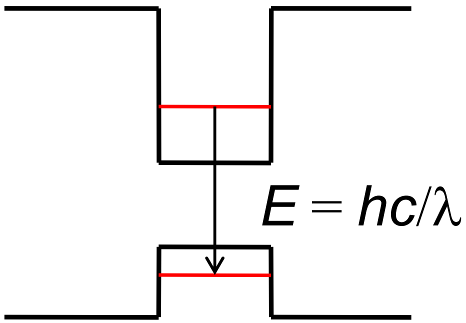
Spectral domain

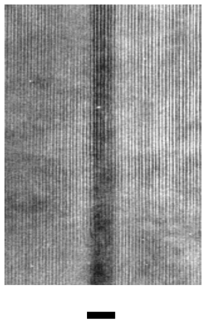


Optoelectronic devices

Active region (LEDs and laser diodes)

Quantum well





3 nm

Increase in the radiative efficiency

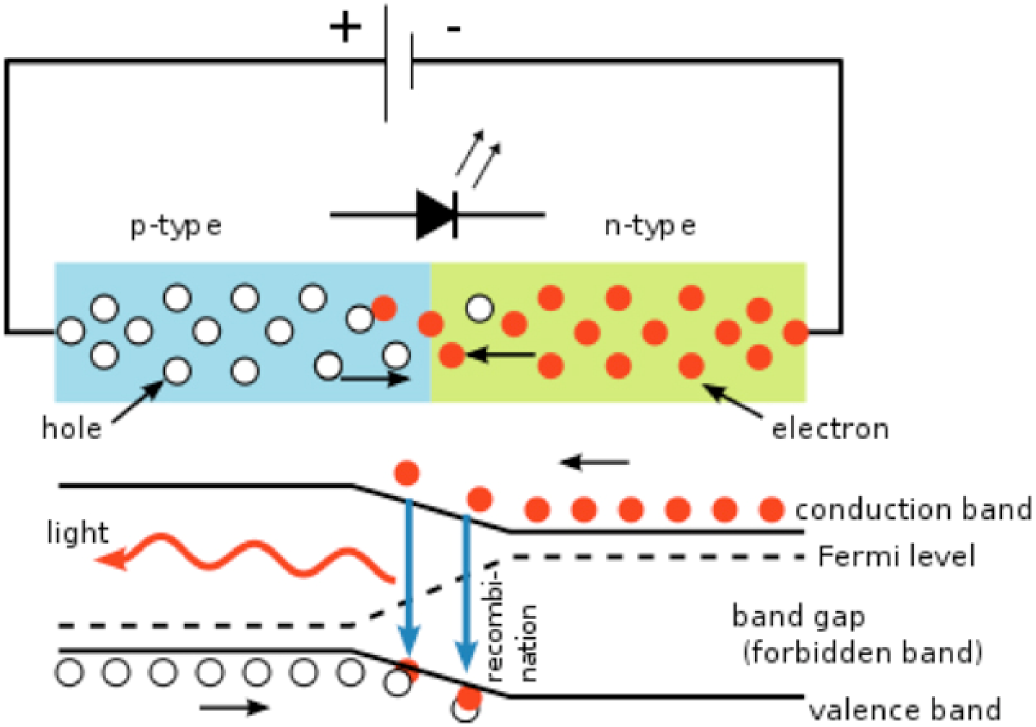
+

Control of the wavelength by tuning:

- ✓ well width (1-20 nm)
- ✓ barrier height
- ✓ bandgap

Material dependent

Light-emitting diodes (LEDs)



⇒ Cf. fall semester for details about the physics of the *p-n* junction!

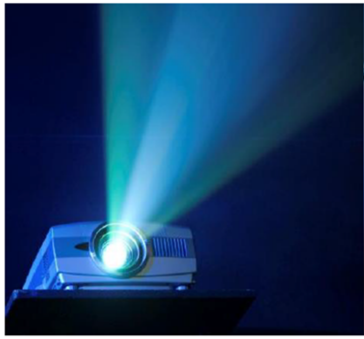
LED applications

Automotive

Forward Lighting

Safety

Consumer



Projection

Tablets I Monitors I TV

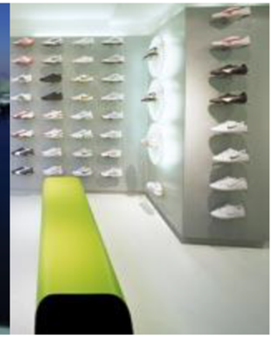
Industry

Video Walls

White Goods

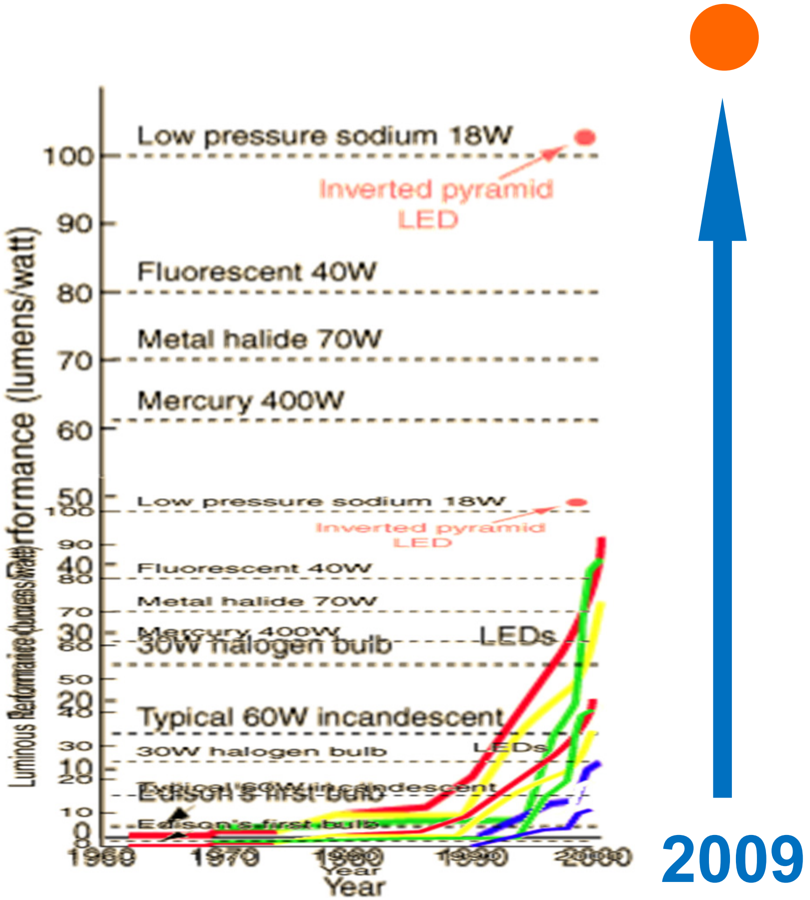
General Lighting

Outdoor Lighting



Shop Lighting

White LEDs for general lighting



2009: 249 lm/W (Nichia)[1]

2014: 300 lm/W (Cree)

145 lm/W at high injection

10 x the luminous efficiency of modern Edison's light bulb

2020 (target): > 200 lm/W at high injection (reached in 2014)

Energy consumption

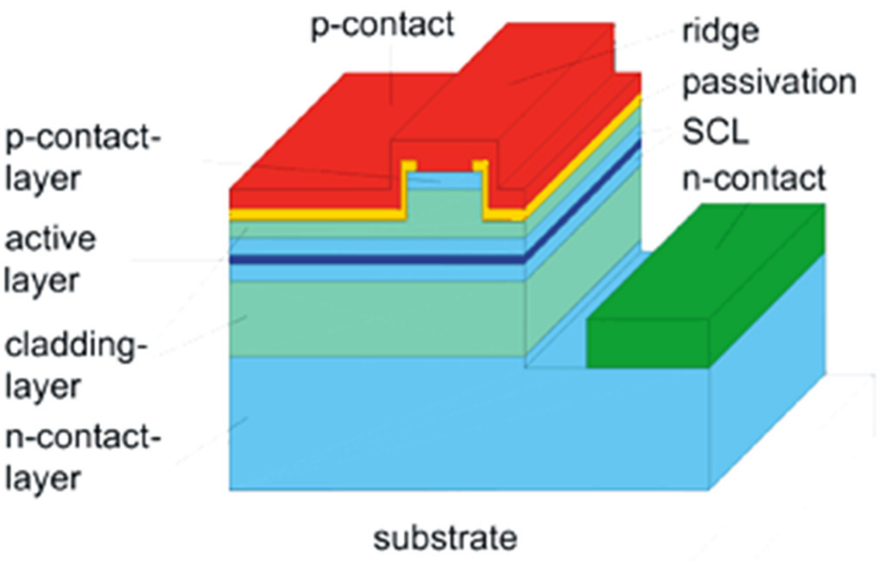
Long lifetime (100 000 h)

Safety

Compactness

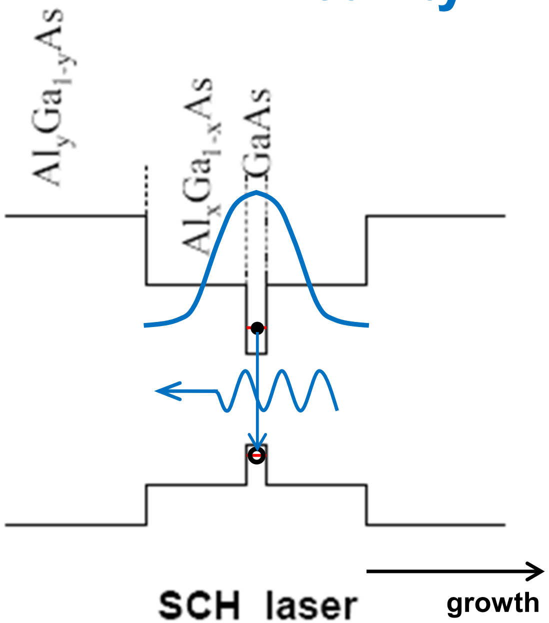
[1] J. Phys. D: Appl. Phys. **43**, 354002 (2010) (> 630 citations)

Semiconductor laser diodes



~ 1 × 3 × 400 μm³

"LED" + cavity

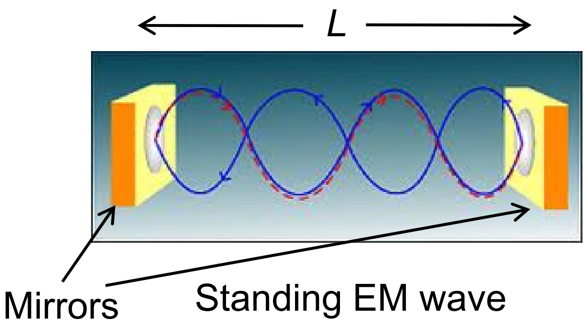


Separate confinement heterostructure (SCH):

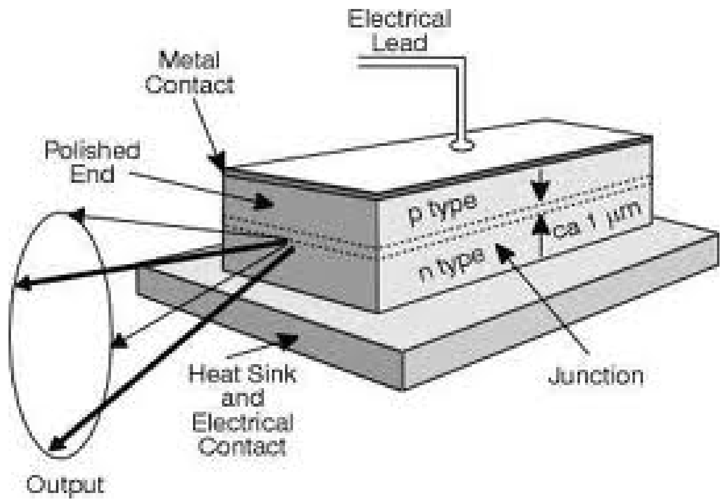
(i) waveguide for light confinement (⊥ growth axis)

(ii) quantum well for electronic charge confinement

Semiconductor laser diodes

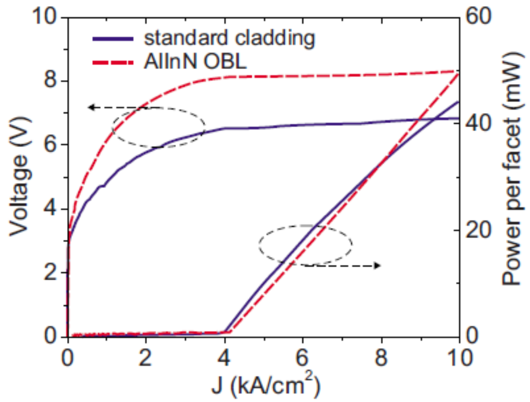


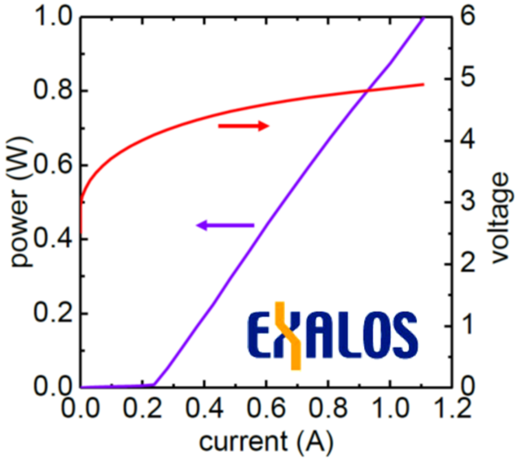
Resonant cavity
⇒ optical feedback

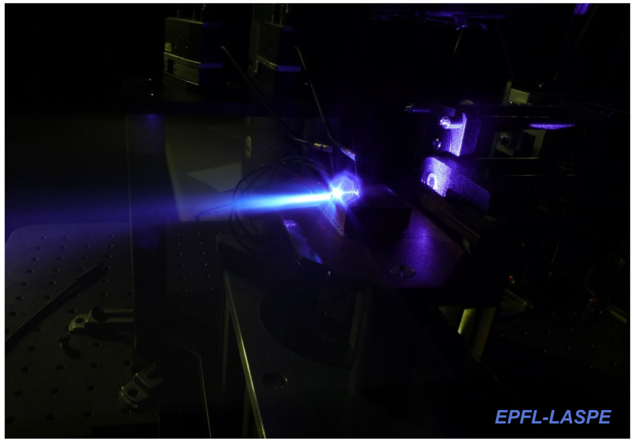


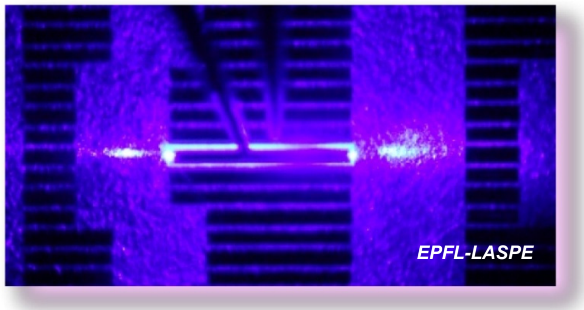
Semiconductor
≡ gain medium

Semiconductor laser diodes



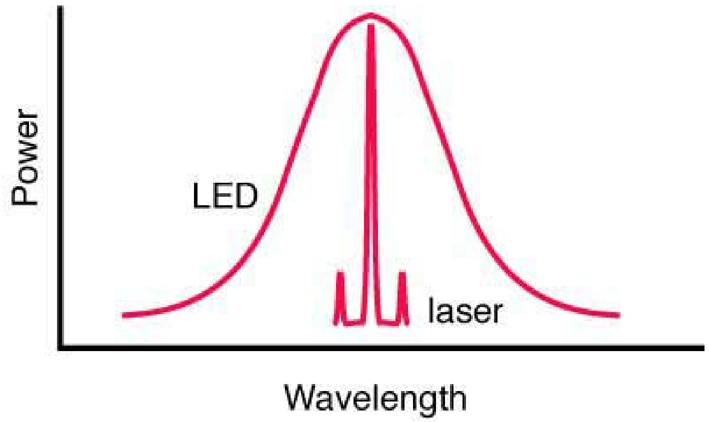


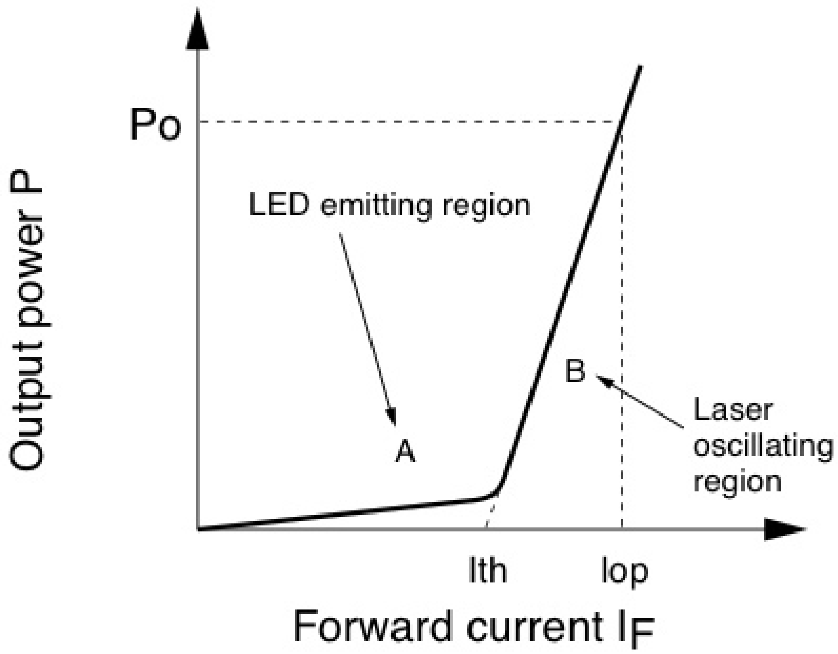




Threshold current ⇨ stimulated emission

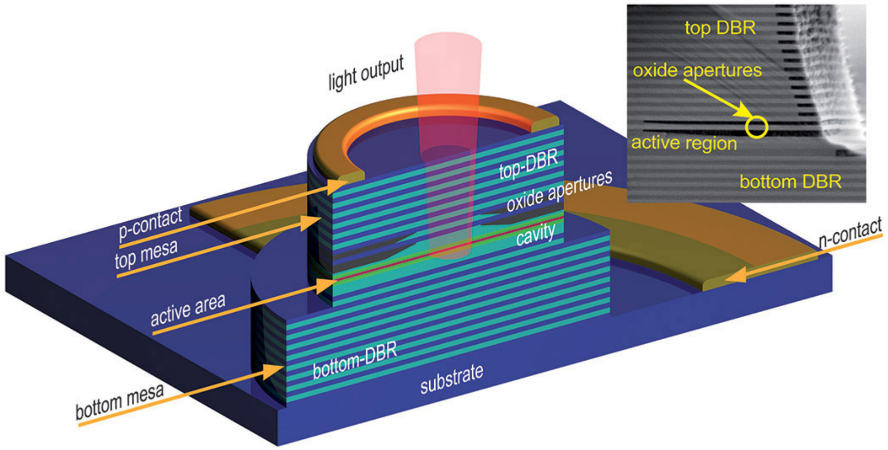
Semiconductor laser diodes



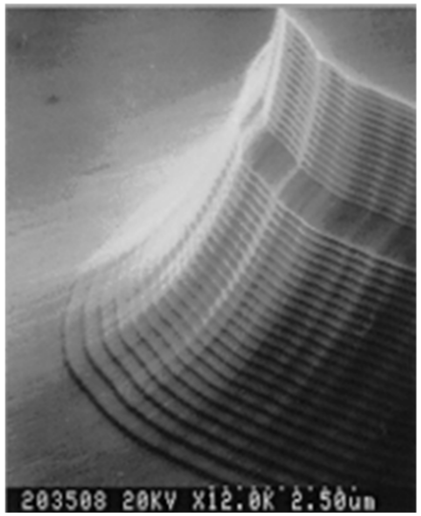


Output power vs. Forward current (P-I_F)

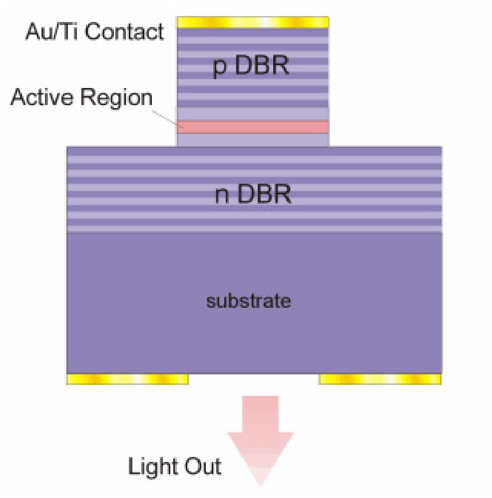
Surface emitting laser diodes

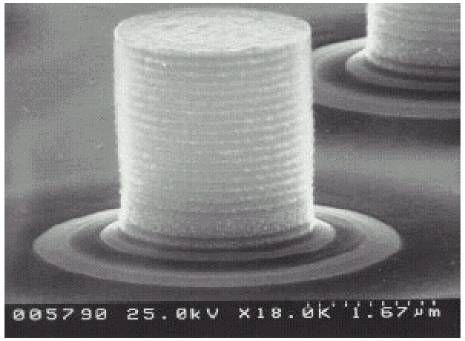


Fabry-Perot cavity formed by two Bragg mirrors

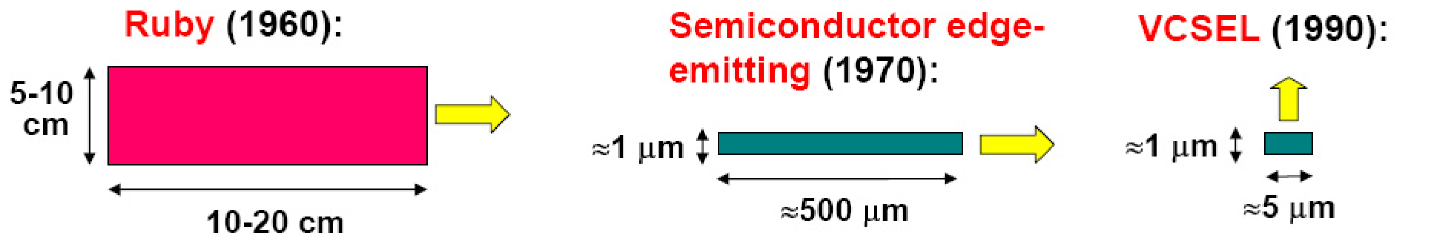


Surface emitting laser diodes





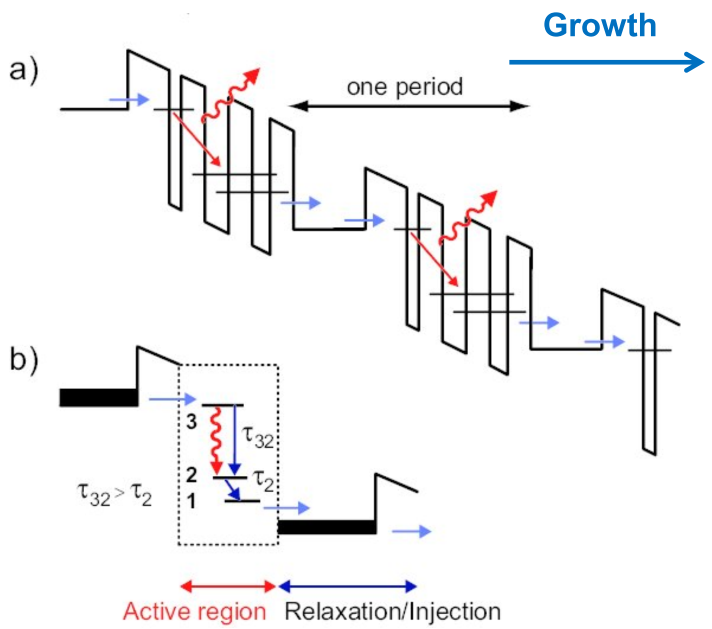
Fabry-Perot cavity formed by two Bragg mirrors

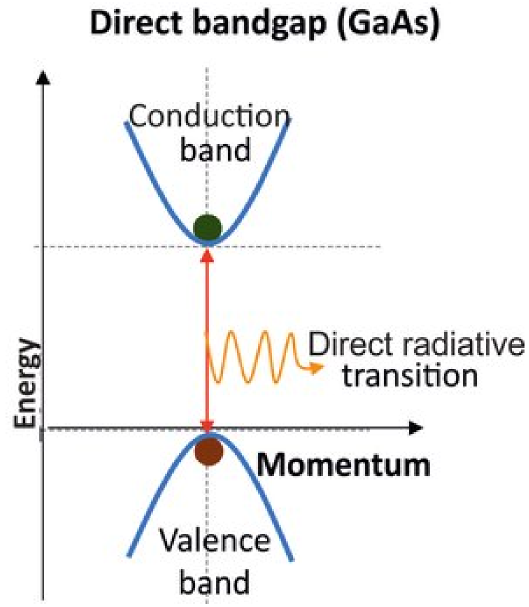


Pulsed operation

Reduced footprint

Quantum cascade lasers





Intersubband/intraband transitions

Interband transitions

Unipolar device: photon emission without *p-n* junction

Alpes Lasers

J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, *Quantum Cascade Laser*, Science **264**, 553, (1994) (> 4300 citations)

Nanostructures and nanocavities

Indistinguishable single photon sources

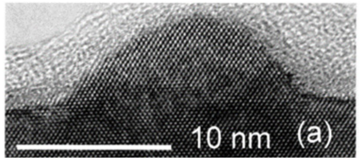
Source of “flying qubits” for quantum information

ARTICLES
PUBLISHED ONLINE: 7 MARCH 2016 | DOI: 10.1038/NPHOTON.2016.23
nature photonics

Near-optimal single-photon sources in the solid state

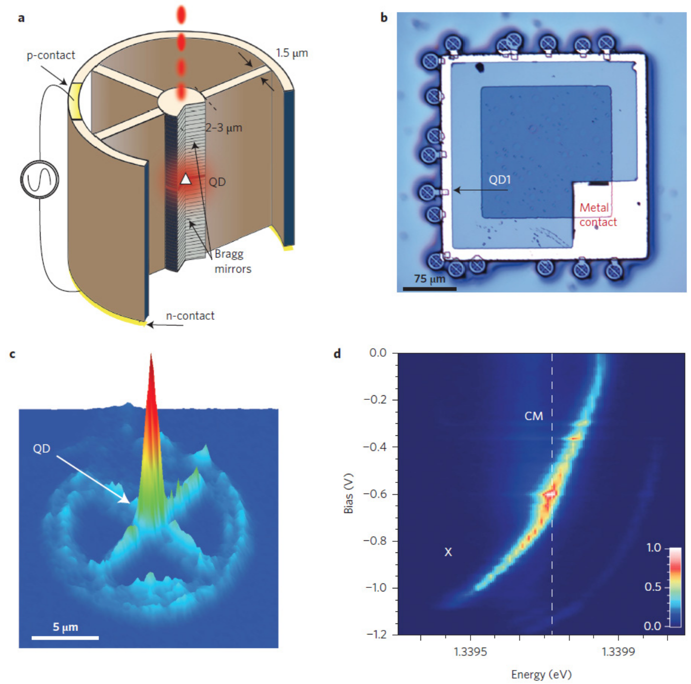
N. Somaschi[1†], V. Giesz[1†], L. De Santis[1,2†], J. C. Loredo[3], M. P. Almeida[3], G. Hornecker[4,5], S. L. Portalupi[1], T. Grange[4,5], C. Antón[1], J. Demory[1], C. Gómez[1], I. Sagnes[1], N. D. Lanzillotti-Kimura[1], A. Lemaître[1], A. Auffeves[4,5], A. G. White[3], L. Lanco[1,6] and P. Senellart[1,7*]

Nat. Phot. **10**, 340 (2016) (> 880 citations)



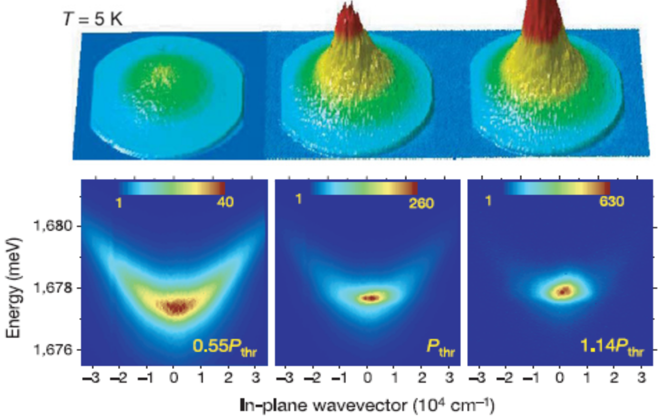
PRL **84**, 733 (2000)
(> 470 citations)

- Under resonant excitation, $g^{(2)}(0) = 0.0028 \pm 0.0012$ together with an indistinguishability of 0.9956 ± 0.0045
- Photon extraction efficiency of 65%
- Brightness 20 times larger than any source of equal quality



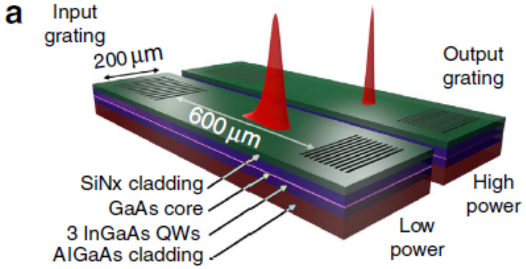
Exciton-polaritons in cavities and waveguides

Bose-Einstein condensation in the solid-state



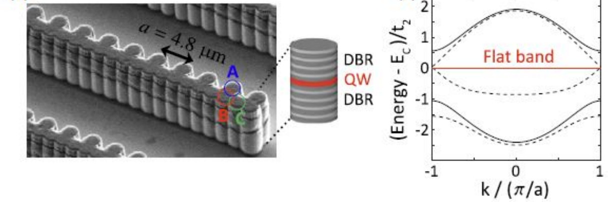
Nature **443**, 409 (2006) (> 2500 citations)

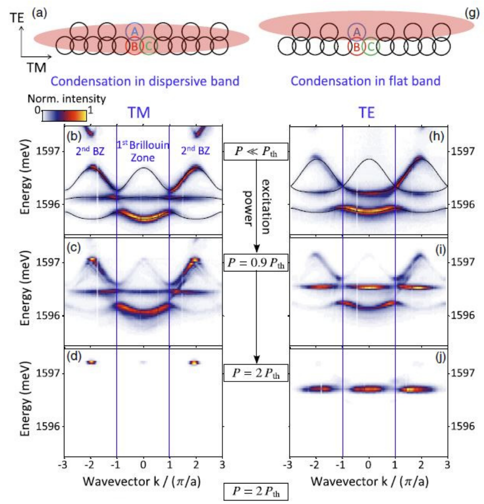
Ultra-low-power hybrid light-matter solitons



Nat. Commun. **6**, 8317 (2015)

Bose condensation in coupled pillars (1D lattice) forming a flat band

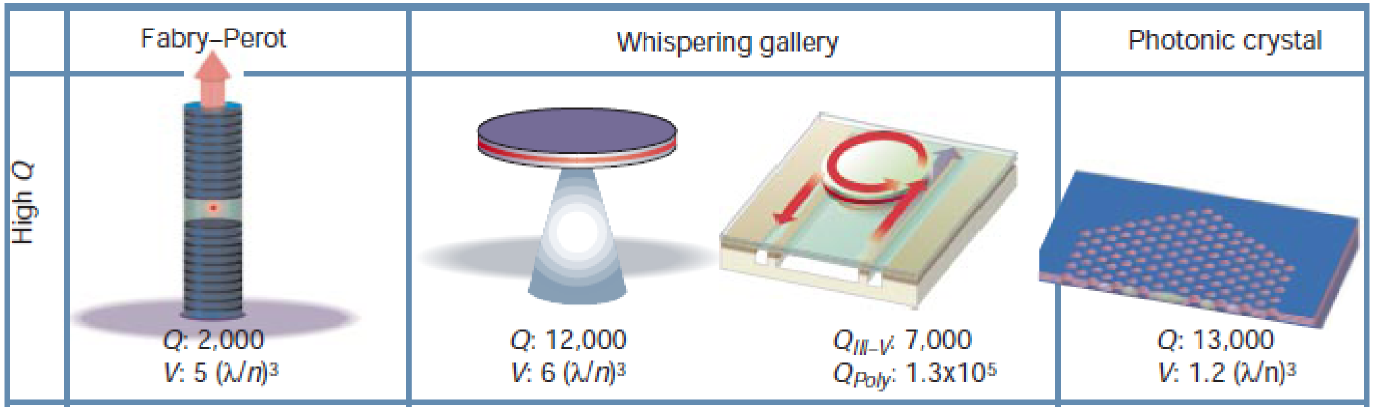




Phys. Rev. Lett. **116**, 066402 (2016)
(> 260 citations)

Micro-(nano-)cavities for light-matter coupling

Physics of small mode volume dielectric cavities coupled to 0D emitters (quantum dots)



F_p= 32 F_p= 150 F_p= 1400

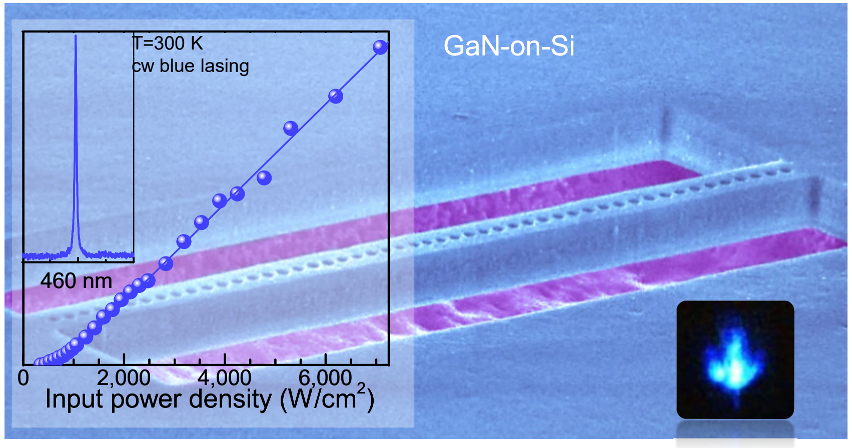
K. J. Vahala, Nature (London) **424**, 839 (2003) (> 4340 citations)

The Purcell factor (F_p) indicates the increase in the spontaneous emission rate of a single emitter inserted in a cavity compared to a conventional bare medium

E. M. Purcell, Phys. Rev. **69**, 681 (1946) (> 3910 citations)

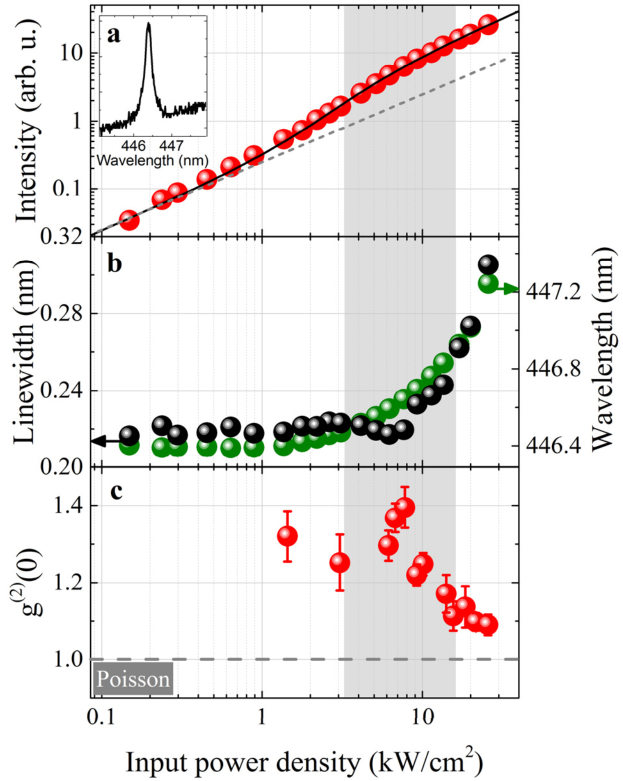
Nanolasers for probing ultimate lasing features

Physics of high-β nanolasers



β: coupling efficiency of spontaneous emission into a lasing mode (here β >> 0.1)

- Explore the ultimate lasing properties in all-dielectric nanocavities (quantum optics)
- On-chip small footprint light sources for photonic integrated circuits and optical interconnects (data centers)



$$g^{(2)}(\tau) = \frac{\langle I(t)I(t-\tau)\rangle}{\langle I(t)\rangle^2}$$

Nano Lett. **15**, 1259 (2015); Nat. Commun. **9**, 564 (2018)

Nobel prizes in physics & chemistry

The Nobel Prize in Physics 2000

Photo from the Nobel Foundation archive.

Zhores I. Alferov

Prize share: 1/4

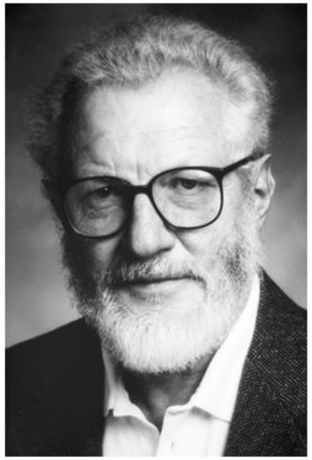


Photo from the Nobel Foundation archive.

Herbert Kroemer

Prize share: 1/4

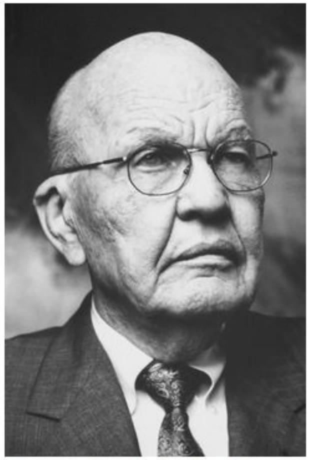


Photo from the Nobel Foundation archive.

Jack S. Kilby

Prize share: 1/2

The Nobel Prize in Physics 2000 was awarded "for basic work on information and communication technology" with one half jointly to Zhores I. Alferov and Herbert Kroemer "for developing semiconductor heterostructures used in high-speed- and opto-electronics" and the other half to Jack S. Kilby "for his part in the invention of the integrated circuit."

The Nobel Prize in Physics 2014

© Nobel Media AB. Photo: A. Mahmoud

Isamu Akasaki

Prize share: 1/3

© Nobel Media AB. Photo: A. Mahmoud

Hiroshi Amano

Prize share: 1/3

© Nobel Media AB. Photo: A. Mahmoud

Shuji Nakamura

Prize share: 1/3

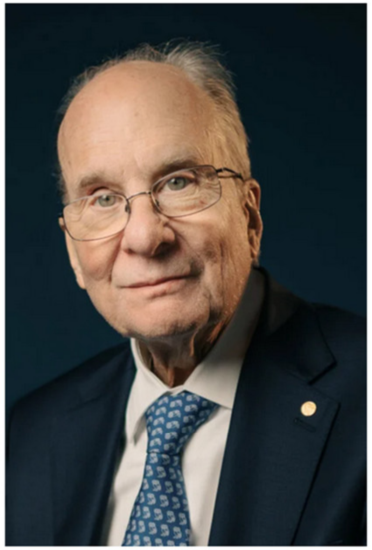
The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources."

Nobel Prize in Chemistry 2023

© Nobel Prize Outreach. Photo: Clément Morin

Moungi G. Bawendi

Prize share: 1/3



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Louis E. Brus

Prize share: 1/3

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Aleksey Yekimov

Prize share: 1/3

The Nobel Prize in Chemistry 2023 was awarded to Moungi G. Bawendi, Louis E. Brus and Aleksey Yekimov "for the discovery and synthesis of quantum dots"