Semiconductor light sources

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Assignatura: Laser systems and applications
Titulacions: Màster Universitari Erasmus Mundus en Enginyeria Fotònica, Nanofotònica i Biofotònica (pla 2010)
Màster Universitari en Fotònica (pla 2013)
Curs: 1r Quadrimestre: 2n
Escola Tècnica Superior d’Enginyeria de Telecomunicació de Barcelona (ETSETB)

Idioma: Anglès
01/01/2022
Semiconductor light sources

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SCHEDULE OF THE COURSE

Semiconductor light sources
- 2 (15/12/2020) LEDs and semiconductor optical amplifiers.
- 3 (18/12/2020) Diode lasers.

Laser Material Processing
- 4 (22/12/2020) High power laser sources and performance improving novel trends
- 5 (12/1/2021) Laser-based material macro processing.
- 6 (15/1/2020) Laser-based material micro processing.

Small lasers, biomedical lasers and applications
- 7 (19/1/2021) Small lasers.
- 8 (22/1/2021) Biomedical lasers.

Laser models
- 9 (26/1/2021) Laser turn-on and modulation response.
- 10 (29/1/2021) Optical injection, optical feedback, polarization.

- 11 (2/2/2021) Students’ presentations.
- 12 (5/2/2021) Students’ presentations.
- 9/2/2021: Exam

Lecturers: C. Masoller, M. Botey
Learning objectives

- Understand the physics of semiconductor materials and the electron-hole recombination mechanisms that lead to the emission of light.

- Learn about the operation principles of light emitting diodes (LEDs) and semiconductor optical amplifiers (SOAs).

- Become familiar with the operation principles and characteristics of laser diodes (LDs).
Outline: Semiconductor light sources

- Introduction
- Light-matter interactions in semiconductor materials
- Light Emitting Diodes (LEDs)
- Semiconductor optical amplifiers (SOAs)
- Laser diodes (LDs)
The start of the laser diode story: the invention of the transistor

Nobel Prize in Physics 1956 “For their research on semiconductors and their discovery of the transistor effect”. The invention of the transistor in 1947 lead to the development of the semiconductor industry (microchips, computers and LEDs –initially only green, yellow and red).
The first working laser: 60 years ago

- In 1960 (43 years after Einstein predicted stimulated emission) Theodore Maiman demonstrated the first working laser and called **MASER**, for "Microwave Amplification by Stimulated Emission of Radiation".
- Maiman's ruby laser emitted, for the first time, **coherent light**: light waves with the same wavelength and phase.
- The paper was published in Nature (at that time a new, low-impact journal).

A collection of 60 significant laser articles published by the Optical Society (OSA) can be found here: https://www.osapublishing.org/lasers/60laserarticles.cfm
The first laser that emitted visible light

- In 1957 Arthur Schawlow and Charles Townes used two highly reflecting mirrors as a resonant optical cavity.
- This allowed to take maser action from microwaves to visible wavelengths.
- In 1958 they published (Physical Review) their findings and submitted a patent application for the so-called optical maser.
- In 1960 the patent was warded in to Arthur Schawlow and Charles Townes.
- In 1981 Schawlow was awarded the Nobel Prize in Physics for the development of laser spectroscopy.
The first semiconductor (diode) laser

- **1962** (electric pump, pulsed operation, cryogenic temperatures).

- On July 1962, at a conference, R. J. Keyes (MIT) reported observing intense luminescence with a quantum efficiency of ~85% from gallium arsenide (GaAs) junctions at 77 K.

- Within months four research teams in the USA almost simultaneously reported injection lasers based on GaAs.

- Very fast race: three papers were published in the same volume of Applied Physics Letters and the fourth one, in Physical Review Letters.
Race to the diode laser

Source: Optics and Photonics News, October 2020
The first tunable laser

- Demonstrated in **1966** by Mary Spaeth, an engineer at Hughes Aircraft.
- It used as gain medium organic dyes dissolved in organic solvents.
- Pumped with a ruby laser, laser pulses from dyes were emitted.
- The dye molecules had broad gain bandwidths, and each had its own spectrum, which allowed a wide range of wavelengths.
- In **1967**, Bernard Soffer and William McFarland (at Maiman’s company, Korad), replaced one mirror of the laser cavity by 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*
In the 60’ & 70’: semiconductor lasers where “a solution looking for a problem”

- Practical lasers require continuous-wave (CW) operation at room temperature (RT), ideally with electric pumping (“laser diode”), and reasonably long lifetime.
- CW RT emission was achieved in **1970**.
- The performance of early laser diodes was limited by manufacturing techniques.

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

*Source: Optics & Photonics News, May 2012*
In the last 60 years, huge variety of lasers have been fabricated

Types of lasers, according to the gain medium:

- **Semiconductor lasers**: the active medium is a *direct* semiconductor. Electrically pumped: **diode lasers**.
  - In 2020 they account for the **42%** of the total laser market.
- **Solid state lasers**: the active medium is a glass or crystalline "host" material, to which “dopants” are added. Optically pumped, using a flash lamp or a laser diode.
- **Fiber lasers**: the active medium is a doped optical fiber. They are optically pumped.
- **Gas lasers**: an electric current discharged through a gas produces coherent light (CO₂, HeNe, Excimer).

*Source: Wikipedia*
Energy efficiency

- Early CO\textsubscript{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 development of diode lasers, which in the early 80s achieved 10\% efficiency.
- Nowadays laser diodes can achieve ~70\% efficiency.
# Laser Power

The continuous or average power required for some uses:

<table>
<thead>
<tr>
<th>Power</th>
<th>Use</th>
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</thead>
<tbody>
<tr>
<td>1–5 mW</td>
<td>Laser pointers</td>
</tr>
<tr>
<td>5 mW</td>
<td>CD-ROM drive</td>
</tr>
<tr>
<td>5–10 mW</td>
<td>DVD player or DVD-ROM drive</td>
</tr>
<tr>
<td>100 mW</td>
<td>High-speed CD-RW burner</td>
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<tr>
<td>250 mW</td>
<td>Consumer 16× DVD-R burner</td>
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<tr>
<td>400 mW</td>
<td>Burning through a jewel case including disc within 4 seconds[^84]</td>
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<tr>
<td></td>
<td>DVD 24× dual-layer recording[^85]</td>
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<tr>
<td>1 W</td>
<td>Green laser in Holographic Versatile Disc prototype development</td>
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<tr>
<td>1–20 W</td>
<td>Output of the majority of commercially available solid-state lasers used for micro machining</td>
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<tr>
<td>30–100 W</td>
<td>Typical sealed CO₂ surgical lasers[^86]</td>
</tr>
<tr>
<td>100–3000 W</td>
<td>Typical sealed CO₂ lasers used in industrial laser cutting</td>
</tr>
</tbody>
</table>

[^84]: [Source](https://example.com)  
[^85]: [Source](https://example.com)  
[^86]: [Source](https://example.com)
Four categories according to the laser ability to produce damage in exposed people.

- **A Class 1** laser is safe under all conditions of normal use. A Class 1M laser is safe except when passed through magnifying optics such as microscopes and telescopes.

- **A Class 2** laser is considered to be safe because the blink reflex (glare aversion response to bright lights) will limit the exposure to no more than 0.25 seconds. It only applies to visible lasers (400–700 nm). Class-2 lasers are limited to cw 1 mW, or more if the emission time is less than 0.25 s.

- **A Class 3R** laser is considered safe if handled carefully, with restricted beam viewing. Visible cw lasers in Class 3R are limited to 5 mW. A Class 3B laser is hazardous if the eye is exposed directly, but diffuse reflections are not harmful.

- **Class 4** is the most dangerous class of laser. It includes all lasers that exceed the Class 3B. A class 4 laser can burn the skin, or cause permanent eye damage.
Laser Applications

- Optical communications (Datacom, telecom)
- Industrial (material processing, sensors)
- Medical (cosmetic, diagnosis, treatment)
- Military (weapons, security)
- Consumer products (printers, pointers, DVDs, barcode scanners)
- Scientific (quantum computing, optical tweezers, etc.)
2019 laser revenues

- Medical & Aesthetic: $1.2B
- Instruments & Sensors: $1.3B
- Scientific Research & Military: $1.8B
- Entertainment, Displays, & Printing: $0.5B
- Materials Processing & Lithography: $6.1B
- Communications & Optical Storage: $4.1B

Source: Laser Focus World
Laser diodes: widely used in Datacom and Telecom (datacenters and optical communication systems)

No laser ⇒ No internet!

Figure 1. Optic fibers made of glass make up the circulatory system of our communication society. There is enough fiber to encircle the globe more than 25,000 times.

Source: www.nobelprize.org
Auto LIDAR: one of the hottest laser-based technologies

- Light detection and ranging (LIDAR) key for enabling autonomous self-driving cars.
- Radar has lower resolution than Lidar; Lidar has advantages over camera systems, which have trouble in low-lighting.
- LIDAR is still expensive, but prices should continue to drop.
- Two operation principles:
  - Time-of-flight (ToF)
  - Frequency-modulated continuous wave (FMCW) extracts time and velocity information from the frequency shift of returning light (Doppler).
Main challenges for advancing Auto Lidar technology

Development of:

- Compact, low-cost, high-power coherent light sources.
- Compact, low-cost optics and detectors for effective collection of light.
- Fast and reliable signal-processing algorithms for identifying and tracking moving objects.

Find out more: OFC 2019 Key note speakers
Mial Warran, “A LIDAR in Every Garage”
https://www.osa.org/en-us/media_library/plenary_keynote_sessions/?videoid=6037627791001

Dmitri Dolgov, "From Self-driving Cars to a Vision for Future Mobility":
https://www.osa.org/en-us/media_library/plenary_keynote_sessions/?videoid=6014512279001
Lasers used for fabricating smartphones

<table>
<thead>
<tr>
<th>Laser Types</th>
<th>Machine Processes</th>
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<tr>
<td>Fiber laser</td>
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<tr>
<td>UV solid-state laser</td>
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<tr>
<td>Solid-state laser</td>
<td>Pattern</td>
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<tr>
<td>CO₂ laser</td>
<td>Holes</td>
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<tr>
<td>Ultrashort pulse laser</td>
<td></td>
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<tr>
<td>UV excimer laser</td>
<td></td>
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<tr>
<td>IR diode laser</td>
<td></td>
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</tbody>
</table>

**Touchscreen**
- Cutting of extremely thin, hard cover glass
- Cutting of touchscreen foil
- Structuring of conducting layers

**Screen**
- Generation of polycrystalline layers
- Encapsulation of laminated glasses

**Battery**
- Welding of battery case
- Marking logo, data-matrix-code, and serial number

**Circuit board**
- Structuring of conductor tracks
- Cutting of foil circuit boards
- Drilling of contact holes

**Housing**
- Cutting of housing
- Marking logo and serial number

Source: SPIE
Laser additive manufacturing (LAM)

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

- LAM covers a broad family of technologies that use laser light to 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.

- LAM 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.

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

Source: SPIE
How intense can a laser pulse be?

Chirped Pulse Amplification (CPA): Physics Nobel prize 2018

Source: www.nobelprize.org
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.
CPA allowed for high-intensity laser pulses

Several methods were developed for emitting extremely powerful short laser pulses, but then development stopped – it was not possible to amplify the light pulses further without damaging the amplifying material.

Extreme Light Infrastructure (ELI) is a European project with three sites that will be completed in a few years.

The world's first functioning laser was built by the American physicist Theodore Maiman.

Source: www.nobelprize.org
How short can a laser pulse be?

Figure 4. The short pulses from a femtosecond laser (right) cause less damage in the material than the million-times longer pulses from a nanosecond laser (left). Ultrashort and intense laser pulses are used in eye surgery, data storage and the manufacture of medical stents for operations in the body's vessels.

Source: www.nobelprize.org
Photo-lithography (optical or UV lithography)

- Is a process used in **microfabrication**, to pattern parts on a thin film or on the bulk of a substrate (called wafer).
- It is the standard method of printed circuit board and microprocessor fabrication.
- Fabricating very small structures requires light sources with very short wavelengths.
- By exposing a thin film or a wafer to **UV light (excimer laser)**, small patterns can be created.
- Extreme UV light ($\lambda \approx 13-14$ nm) allows building nano-structures on chips.

*Why do we want to build nano-structures on chips?*
Moore’s law: the performance of microelectronics (the number of transistors on a chip) doubles every 18-24 months.
The development of excimer laser lithography has played a critical role in the continued advance of Moore's law.
VCSELs (vertical-cavity surface-emitting lasers) are used for sensors in smartphones and iPhones.

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 unlock the phone.

Source: SPIE news room, April 2018
Laser diodes are a big part of the laser market

Source: Strategies Unlimited
Why are laser diodes so popular?

- Low cost because of mature semiconductor technology.
- Do not require fragile enclosures or mirror alignment: The refractive index contrast between the semiconductor material (~3.5) and the surrounding air causes the cleaved surfaces to act as reflectors.
- Small size.
- Electrically pumped: convert an electric current in a photon flux.
- High efficiency (the % of conversion of electric to optical power – the “wall-plug efficiency” – depends on wavelength and temperature).
Semiconductor materials cover a wide range of wavelengths. Importantly, laser diodes emit in the infrared regions where silica optical fiber has minimum dispersion or transmission loss.

Source: Thorlabs
Common laser diode wavelengths and uses

Visible light  [edit]
- 405 nm – InGaN blue-violet laser, in Blu-ray Disc and HD DVD drives
- 510–525 nm – InGaN Green diodes recently (2010) developed by Nichia and OSRAM for laser projectors.[21]
- 635 nm – AlGaInP better red laser pointers, same power subjectively twice as bright as 650 nm
- 650–660 nm – GaInP/AlGaInP CD and DVD drives, cheap red laser pointers
- 670 nm – AlGaInP bar code readers, first diode laser pointers (now obsolete, replaced by brighter 650 nm and 671 nm DPSS)

Infrared  [edit]
- 760 nm – AlGaInP gas sensing: O₂
- 785 nm – GaAlAs Compact Disc drives
- 808 nm – GaAlAs pumps in DPSS Nd:YAG lasers (e.g., in green laser pointers or as arrays in higher-powered lasers)
- 848 nm – laser mice
- 980 nm – InGaAs pump for optical amplifiers, for Yb:YAG DPSS lasers
- 1,064 nm – AlGaAs fiber-optic communication, DPSS laser pump frequency
- 1,310 nm – InGaAsP, InGaAsN fiber-optic communication
- 1,480 nm – InGaAsP pump for optical amplifiers
- 1,512 nm – InGaAsP gas sensing: NH₃
- 1,550 nm – InGaAsP, InGaAsN fiber-optic communication
- 1,625 nm – InGaAsP fiber-optic communication, service channel
- 1,654 nm – InGaAsP gas sensing: CH₄
- 1,877 nm – GaInAsSb gas sensing: H₂O
- 2,004 nm – GaInAsSb gas sensing: CO₂
- 2,330 nm – GaInAsSb gas sensing: CO
- 2,680 nm – GaInAsSb gas sensing: CO₂
- 3,030 nm – GaInAsSb gas sensing: C₂H₂
- 3,330 nm – GaInAsSb gas sensing: CH₄

Diode laser for plastic and metal welding, brazing, cladding, and medical applications that comes in a small package. It offers a choice of wavelengths across the 9xx nm spectral range and delivers 100 W power out of a 105-μm core fiber.

Source: IPG Photonics
Outline

- Introduction
- **Light-matter interactions in semiconductor materials**
  - Fundamentals of semiconductors
  - Carrier recombination processes
  - Semiconductor gain
- LEDs
- Semiconductor optical amplifiers
- Diode lasers

What *is* a semiconductor material?  
What makes a semiconductor a good light emitter?  
What makes a semiconductor a good light detector?
What is a semiconductor?

In a semiconductor the bandgap between the conduction band and the valence band is smaller than in an insulator.

⇒ A semiconductor sometimes behaves as a conductor (metal) and sometimes, as an insulator.
A more precise definition

A semiconductor has a bandgap that is small enough so electrons in the valence band can be thermally excited across the band gap \( \Rightarrow \) observable thermal conductivity if \( T > 0 \).

\[ E_g < 2-3 \text{ eV} \]

\[ E_g \text{ at RT for some semiconductor materials:} \]
- Si (silicon): 1.12 eV
- Ge (germanium): 0.67 eV
- GaAs (Gallium arsenide): 1.42 eV
- GaN (Gallium nitride): 3.5 eV
# Semiconductor materials

![Periodic Table of Elements](image)

### Table

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<th>Atomic Weight</th>
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For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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Source: Ptable.com
Semiconductor materials are classified as

- **Intrinsic**: the semiconducting properties occur naturally.
- **Extrinsic**: the semiconducting properties are manufactured.
  - **Doped**: the addition of 'foreign' atoms.
    - **n-type**: has an excess of electrons.
    - **p-type**: shortage of electrons (excess of 'holes').
  - **Compound semiconductors**: composed by different semiconductor materials.

- **Direct**
- **Indirect**
Doped semiconductors

- Group III–V semiconductors use group VI atoms as donors and group II atoms as acceptors.

- Group IV semiconductors use group V atoms as donors and group III atoms as acceptors.

Probability of occupancy of the electronic states (Fermi–Dirac distribution)

The shade follows the Fermi–Dirac distribution (black = all states filled, white = no state filled).

- In metals and semimetals the Fermi level, $E_F$, lies inside the conduction band.
- In insulators and semiconductors $E_F$ is inside the band gap.
- In semiconductors the bands are near enough to the Fermi level to be thermally populated with electrons or holes.

A “2-level atom” versus a semiconductor material

2-level atom

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

In a semiconductor: electron/hole pairs & energy bands

Bandgap energy $E_g$

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
Energy and momentum of a photon of frequency $\nu$

Energy $E = h \nu \quad E = \hbar \omega$

Momentum $p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda}$

$k = 2\pi/\lambda \Rightarrow p = (h/2\pi)k$

Frequency of a photon that has energy equal to the band-gap energy, $E_g$.

$\nu_g = E_g/h, \quad \lambda_g = c/\nu_g \Rightarrow \lambda_g = hc/E_g \Rightarrow \lambda_g = \frac{1.24}{E_g} \, \lambda_g \, (\mu\text{m}) \text{ and } E_g \, (\text{eV})$

Wavelength of a photon that has $E=E_g$.

Planck constant: $h=4.13 \times 10^{-15}$ eV s
Energy - momentum relation of direct and indirect semiconductors

Near the band edges (bottom/top of the conduction/valence):

\[ p = \left(\frac{\hbar}{2\pi}\right) k \]
\[ E = E_c + \frac{\hbar^2 k^2}{2m_c} \]
\[ E = E_v - \frac{\hbar^2 k^2}{2m_v} \]

Parabolic band approximation

\( m_c, m_v \): effective mass of an electron (of a hole) in the CB (in the VB).

**Gallium arsenide (GaAs)**

**Silicon (Si)**

Conservation of momentum: \( p_e \approx p_h \) (\( p_{\text{photon}} \approx 0 \) – no mass) \( \Rightarrow k_e \approx k_h \)

\( \Rightarrow \) Optical transitions are **vertical** in \( k \) space
Interactions between photons and electron-hole pairs (carriers) in direct semiconductors

Absorption

The electron absorbs a photon and jumps to conduction band generating a hole in the valence band.

\[ h\nu \geq E_g \]

\[ k \]

e/h spontaneous recombination

The electron and the hole recombine and release energy by emitting a photon.

\[ h\nu \]

\[ k \]

e/h stimulated recombination

The energy of the photon \( h\nu \) has be at least equal to the energy of the gap \( E_g \) in order to be absorbed or emitted.
In 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.

Main advantage: Silicon is an inexpensive material
Compound semiconductors

By combining different semiconductors, materials with different optical properties can be fabricated.
To fabricate a compound semiconductor it is important to properly match the lattice constant

- By adjusting the composition of the compound material, its lattice constant can be adjusted to match the lattice constant of the substrate.

- This is important because
  - A good match allows to grow high-quality crystal layers.
  - Lattice mismatch results in crystalline imperfections, which can lead to \textit{non-radiative recombination}.
  - Lattice mismatch reduces the laser lifetime.
Binary compounds

III - V

II - IV

<table>
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<tr>
<th>Material</th>
<th>$E_g$ (eV)</th>
<th>$\lambda_g$ ($\mu$m)</th>
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</table>
Ternary compounds

- GaAs → AlAs as $x=0 \rightarrow 1$
- A nearly horizontal line is very important: it means ternary compounds with the same lattice constant, which allows to fabricate high-quality crystal layers.

A solid (dashed) line means direct (indirect) 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 \((\text{In}_{1-x}\text{Ga}_x)(\text{As}_{1-y}\text{P}_y)\).
Materials and wavelengths

- **UV and blue (445 - 488 nm):**
  - First developed in the 1990s (more latter)
  - GaInN
  - 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):**
  - $\text{Al}_y\text{Ga}_x\text{In}_{1-x-y}\text{P}/\text{GaAs}$
  - Applications: DVD (650 nm); pointers (635 nm); scanners (635 nm)
Infrared: materials and wavelengths

- **GaAlAs**: 750-904 nm
  - Applications: CD players, high-power uses

- **InGaAs/GaAs**: 915-1050 nm
  - Applications: pump fiber and solid state lasers

- **InGaAsP/InP**: 1100-1650 nm
  - Applications: fiber optic communications
Optical properties of semiconductors

- They are determined by
  - the gain, $G$
  - the absorption coefficient, $\alpha$
  - the refractive index, $n$

- $G$, $\alpha$ and $n$ depend on the electron/hole concentration, known as the "carrier concentration", $N$.

- $N$ can be calculated from
  - the density of available states, $\rho(E)$, $E=h\nu$
  - the occupation factor, $f(E)$: probability that a state $E_c$ in the conduction band is occupied/empty and a state $E_v$ in the valence band ($E_c-E_v=E$) is empty/occupied.

The density of states $\times$ the occupation factor $= N$
Density of states

Density of states in the CB and in the VB: number of states per unit volume, with energy in the interval $E = h \nu$, $E + dE = h \nu + h \delta \nu$. Unit: $[m^{-3}Hz^{-1}]$.

$$\rho_c(E) = \frac{(2m_c)^{3/2}}{2\pi^2h^3}(E - E_c)^{1/2}, \quad E \geq E_c$$

$$\rho_v(E) = \frac{(2m_v)^{3/2}}{2\pi^2h^3}(E_v - E)^{1/2}, \quad E \leq E_v.$$ 

Here $m_c$ ($m_v$) is the effective mass of an electron (of a hole) in CB (in VB).

These expressions assume the **parabolic band approximation**, which is valid for a “bulk” material near the band edges – more latter about non-bulk materials such as quantum wells (QWs) and quantum dots (QDs).
Joint density of states

Density of states with which a \textit{photon} of energy \( E = h \nu \) can “interact” \((E_c - E_v = E)\), assuming a direct semiconductor with parabolic bands.

\[
\rho(E) = \frac{(2m_r)^{3/2}}{\pi \hbar^2} (h \nu - E_g)^{1/2}, \quad h \nu \geq E_g
\]

\[
\frac{1}{m_r} = \frac{1}{m_v} + \frac{1}{m_c}
\]

(to be used latter, to estimate the rates of spontaneous emission, stimulated emission and absorption)
Occupation factor

Intrinsic semiconductor

\[ f(E) = \text{probability of occupancy by an electron} \]

\[ 1 - f(E) = \text{probability of occupancy by a hole (valence band)} \]

\[ f(E) = \frac{1}{\exp\left(\frac{E - E_f}{k_B T}\right) + 1} \quad \text{Fermi function} \quad k_B = 8.6 \times 10^{-5} \text{ eV/K} \]

\[ f(E) \approx \exp\left(-\frac{E_g}{k_B T}\right). \quad T = 300 \text{ K}, \quad E_g = 4 \text{ eV} \Rightarrow f(E) \approx 10^{-55} \text{ (isolator)} \]

\[ E_g = 0.25 \text{ eV} \Rightarrow f(E) \approx 10^{-2} \text{ (conductor)} \]
Electron and hole concentrations in thermal equilibrium:
density of states $\times$ occupation factor

Electrons in CB

$$n(E) = \rho_c(E) f(E)$$

Holes in VB

$$p(E) = \rho_v(E) [1 - f(E)]$$

Same Fermi level

$E_c$

$E_f$

$E_v$
Quasi-Fermi levels

- The **intra-band relaxation time** (ps) is much faster than **inter-band relaxation time** (ns).
- Therefore, electrons in CB (and the holes in VB) are in thermal equilibrium among themselves, but they might not be in mutual equilibrium.
- In this situation, **quasi-Fermi levels** \((E_{fc}, E_{fv})\) describe the occupation factors of CB and VB.

![Diagram showing quasi-Fermi levels with EC, Ec, Eg, Ef, and n(E), p(E)]
Probability of absorption (of a photon) and of emission (of a photon)

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).

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

where $E_2 - E_1 = h\nu$

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.

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

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

In quasi-equilibrium, emission will be more probable than absorption if $f_e(\nu) > f_a(\nu)$. This occurs when the quasi-Fermi levels satisfy the condition $E_{fc} - E_{fv} > h\nu$

Condition for emission > absorption
The p-n junction

- Formed by p-doped and n-doped semiconductors.
- **Mobile** electrons and holes **diffuse**.
- Leave behind a region ("**depletion zone**") that contains only fixed charges.
- These fixed charges create an electric field that obstructs the diffusion of mobile charges.

In thermal equilibrium:

*Source: Wikipedia*
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.

- If the voltage is connected the other way around the electrons and holes retreat even further, making the depletion layer even larger (and the semiconductor becomes an insulator).

First semiconductor lasers were p-n junctions ("Homo-structures")
Carrier-induced waveguide

- The concentration of electrons and holes in the depletion layer modifies the local refracting index, creating an **effective waveguide** that helps to confine the photons.

- **Confinement factor:** percentage of the optical mode that is located in the region where the electrons and holes are (in the “depletion layer”).
Summary

- In a p-n junction, the diffusion of electrons and holes generates a “depletion layer” that contains fixed charges.
- When a positive voltage is applied to the p-region, the electric current can flow across the junction.
- With forward bias electrons and holes recombine at the depletion layer, converting electrical current into light.
- The emitted photons have $h\nu \geq E_g$ ($\lambda \leq \lambda_g = hc/E_g$).
- The carrier mobility (electron diffusion length) is an important characteristic of semiconductor materials.
- A good confinement factor (i.e., concentrating photons and “carriers” -electrons and holes- in the same region) is crucial for efficiency.
Outline

- Introduction
- **Light-matter interactions in semiconductor materials**
  - Fundamentals of semiconductors
  - *Carrier recombination processes*
  - Semiconductor gain
- LEDs
- Semiconductor optical amplifiers
- Diode lasers

Which are the mechanisms that generate “carriers” *(electrons in the CB and holes in the VB)*? How do electrons and holes recombine?
Generation of electrons and holes

Three main mechanisms:
1. Thermal
2. External injection of free electrons (electric “pump”)
3. External injection of photons (optical “pump”)
Generation and recombination of electrons and holes

- Two main types of electronic transitions:
  - **Radiative:** the energy is taken from/by a photon
  - **Ron-radiative:** the energy released from the recombination of an electron/hole pair is taken by a third particle, or it is dissipated as heat.

- Electronic transitions also be classified as:
  - **Band-to-band transitions:**
    - electron/hole generation: a photon is absorbed.
    - e/h recombination: a photon is emitted (stimulated or spontaneous emission).
    - Is the operation principle of conventional semiconductor light sources (LEDs, SOAs, LDs).
  - **Intra-band transitions:** transitions within the conduction band (is the operation principle of quantum cascade lasers-more latter).
  - **Others.**
Other mechanisms of carrier recombination

- **Impurity-to-band (Shockley-Read-Hall trap-assisted recombination):** the electron in transition between bands passes through an energy state (“trap”) created within the band gap by a dopant or by a defect in the crystal lattice. The energy is released in the form of lattice vibration (a “phonon” -thermal energy) or in the form of a photon with $E = h\nu < E_g$.

- **Auger** (electron + hole + third particle): non-radiative, the energy released by the e/h recombination is taken by a third particle.
Electron/hole recombination processes

(a) Shockley-Read-Hall (SRH) recombination: one particle at a time (electron or hole).

(b) Bimolecular recombination: two carriers (electron and hole) simultaneously.

(c) Auger: three particles (2 electrons + 1 hole or 1 electron + 2 holes).

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

- A photon that is emitted by band-to-band recombination has $E=h\nu > E_g$.
- A photon that is emitted through a SRH process has $E = h\nu < E_g$.

(c) Nonradiative: the energy released by band-to-band recombination of an e/h pair is picked up by a third particle (electron or hole) that loses its excess energy to thermal vibrations.
Examples of absorption and emission of photons in a semiconductor

\[ E_g = 1.42 \text{ eV} \]

\[ E_A = 0.088 \text{ eV} \]

\[ E_g = 0.66 \text{ eV} \]

(a) Band-to-band transitions in GaAs can result in the absorption or emission of photons of wavelength \( \lambda_g = \frac{hc}{E_g} = 0.87 \mu\text{m} \). (b) The absorption of a photon of wavelength \( \lambda_A = \frac{hc}{E_A} = 14 \mu\text{m} \) results in a valence-band to acceptor-level transition in Hg-doped Ge (Ge:Hg). (c) A free-carrier transition within the conduction band.
Shockley-Read-Hall radiative recombination is important in indirect-gap semiconductors (where band-to-band radiative recombination probability is very low)

- SRH radiative recombination is responsible for improving the luminescence efficiency of the indirect-gap semiconductors for their applications in LEDs.

- For example, in GaP, N and ZnO impurities act as electron traps.
Carrier recombination rate

\[ \frac{dN}{dt} = -R \]

\[ R = AN + BN^2 + CN^3 \]

- A: Shockley-Read-Hall coefficient
- B: bimolecular recombination coefficient
- C: Auger recombination coefficient

- At low carrier concentration: only SRH is important.
- Auger process becomes significant at high carrier concentration.
- Between the two limits, the bimolecular recombination process is the dominant recombination process.
- \( B \) is orders of magnitude larger in direct than in indirect semiconductors (\( 10^{-10} \) vs \( 10^{-15} \) cm\(^3\)/s).
Carrier lifetime

\[ \tau_N = \frac{N}{R} \]

\[ \frac{dN}{dt} = -R = \frac{N}{\tau_N} \]

Neglecting the dependence of \( \tau_N \) with \( N \):

\[ N(t) = N_0 e^{-t/\tau_N} \]

\[ \frac{1}{\tau_N} = \frac{R}{N} = A + BN + CN^2 = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \]

\( \tau_r \): radiative lifetime
\( \tau_{nr} \): non-radiative lifetime

Typical value for direct semiconductor materials: \( \tau_N \approx 1 \text{ ns} \)
Internal quantum efficiency

\[ \eta_i = \text{Fraction of injected electrons that are converted to photons} \]

\[ \eta_i = \frac{1}{\tau_r} \frac{1}{\tau_N + 1/\tau_{nr}} \]

Using

\[ \frac{1}{\tau_N} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \]

\[ \Rightarrow \eta_i = \frac{\tau_N}{\tau_r} = \frac{\tau_{nr}}{\tau_{nr} + \tau_r} \]

For large \( N \): reduction of \( \eta_i \) due to Auger effect
Outline

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- LEDs
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- Diode lasers

How to estimate the gain of a semiconductor material?
The rates of stimulated emission and absorption are proportional to the carrier concentration and to the flux of photons.

**Gain coefficient** = \((\text{rate of stimulated emission} - \text{rate of absorption}) / \text{incident photon flux}\)

The rates of stimulated emission and absorption are proportional to the carrier concentration and to the flux of photons.

**Reminder:** carrier concentration \(N = \text{density of states} \times \text{occupation factor}\)

\(dN/dt = -R = -N/\tau_N\)
Rates of spontaneous emission, stimulated emission and absorption

\[ r_{sp}(\nu) = \frac{1}{\tau_r} \rho(h\nu) f_e(\nu) \]
\[ r_{st}(\nu) = \phi_\nu \frac{\lambda^2}{8\pi \tau_r} \rho(h\nu) f_e(\nu) \]
\[ r_{ab}(\nu) = \phi_\nu \frac{\lambda^2}{8\pi \tau_r} \rho(h\nu) f_a(\nu) \]

Absorption and emission probabilities:
\[ f_a(\nu) = [1 - f_c(E_2)] f_v(E_1) \]
\[ f_e(\nu) = f_c(E_2)[1 - f_v(E_1)] \]

\( r_{sp}, r_{st} \& r_{ab} : [m^{-3}] \)
\( \phi_\nu : \) Photon flux = number of photons per second per unit area and per Hz) [m^{-2}] 
\( \tau_r : \) radiative lifetime [s]

\( \rho(E) : \) joint density of states [m^{-3} Hz^{-1}]
Net Gain coef. = (rate of stimulated emission – rate of absorption) incident photon flux

\[ \gamma_0(\nu) = \frac{[r_{st}(\nu) - r_{ab}(\nu)]}{\phi_v} \] [cm\(^{-1}\)]

prop to \( \rho(h\nu) \times [f_e(\nu) - f_a(\nu)] \)

\( f_e(\nu) - f_a(\nu) \)

Gain bandwidth

(solid T=0, dash RT)
In a semiconductor the gain depends on the carrier concentration, $N$, and on the temperature, $T$.

InGaAsP at room temperature

The gain bandwidth and the peak value of the gain coefficient increase with the carrier concentration $N$.

In a semiconductor the gain spectrum is asymmetric.
The linear approximation is valid for “bulk” materials for which the parabolic band approximation holds (–more latter about quantum wells and quantum dots).
Transparency condition

- A semiconductor is “transparent” when the net gain is $= 0$.
- One input photon produces one output photon.
Refractive index $n(N, \nu, T)$

It is related to the gain by the Kramers-Kroning relations
$\text{[gain} \sim - \text{Im}(\chi), n \sim \text{Re}(\chi)]$ where $\chi$ is the complex susceptibility.
$\Rightarrow n$ also depends on $N, \nu, \text{and } T$.

At $T=300$ K

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<tr>
<th>Material</th>
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</table>
Summary (1/2)

- Electrons and holes can be generated by internal thermal fluctuations, or by an external source of energy: electrical (injection of electrons) or optical (injection of photons $h\nu > E_g$).

- An electron and a hole can recombine by emitting a photon, or non-radiatively (the released energy is taken by a “phonon” or by a third particle).

- For efficient light emission non-radiative recombination processes need to be minimized.

- The internal quantum efficiency is the fraction of electrons that recombine radiatively (i.e., the radiative / total recombination rate).
Summary (2/2)

- The internal quantum efficiency is maximum for an optimal carrier concentration.
- The gain is proportional to (rate of stimulated emission – rate of absorption).
- The gain bandwidth and the gain peak depend on the carrier concentration and on the temperature.
- At transparency the carrier concentration is such that there is no net gain (one input photon generates one output photon).
What is the operation principle of an LED?
LEDs operation principle: **spontaneous emission**, also known as electro-luminescence (inverse of the photo-electric effect). LEDs emit **incoherent** light.
**Fig. 1.** Principle for light emission in a p-n junction. In a p-n junction biased with a forward voltage, electrons are injected from the n- to the p-side, and holes are injected in the opposite direction. Electrons recombine with holes and light is emitted (spontaneous emission). For efficient diodes it is important that the semi-conductors have direct bandgaps. LEDs with indirect bandgaps require phonon-assisted recombination, which limits the efficiency. The quantum efficiency of a LED is the ratio of the number of emitted photons to the number of electrons passing through the contact in a given time.
The life and times of the LED — a 100-year history

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Many people believe that the LED was discovered 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.
Light emitting diode (LED) operation principle:

Spontaneous emission or electro-luminescence (inverse of the photo-electric effect)

- The emitted wavelength depends on the material used.
- LED’s size < a grain of sand.
- Green, yellow and red LEDs were invented in the 1950s and have been used in displays, “on/off” light indicators, etc.
- Physics Nobel Prize 2014 “for the invention of efficient blue LEDs”.

Source: www.nobelprize.org
Why blue LEDs are so important?

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

Source: www.nobelprize.org
How to obtain white light from a blue LED?

Gallium nitride (GaN) is combined with a fluorescent material.

Modern LEDs have advanced “hetero-structure” designs (more latter about double-hetero-structures and quantum wells)

Source: www.nobelprize.org
Gallium nitride

- GaN is a direct III-V semiconductor.
- It can be grown on a substrate of sapphire or Silicon Carbide (SiC), despite the difference in lattice constants.
- GaN can be doped with silicon to n-type and with magnesium to p-type.
- Unfortunately, doping interferes with the growth process so that GaN becomes fragile.
- GaN has a direct bandgap of 3.4 eV, corresponding to a wavelength in the ultraviolet.
Spectrum of a white LED showing blue light emitted by the GaN-based LED (peak at 465 nm) and the more broadband light emitted by the phosphor (500–700 nm).

LEDs can be used not only for illumination

- LED lights can be switched on and off so fast, that it is imperceptible to the human eye.

- In this way, LEDs can be used for wire-less data transmission to mobile optical receivers.

- Li-Fi: transmitting data at high speeds using visible, ultraviolet, and infrared light (Wi-Fi uses radio frequency).
LED-enabled “smart cities”

Combined with sensor technology and artificial intelligence, LEDs have many uses in “smart cities”.

Source: Optics and Photonics News, November 2018
Typical LED Light output power vs. injected current (LI curve)

- An LED has no emission threshold.
- Saturation at high pump current ("Efficiency droop" due to Auger effect).
LED efficiency

- Optical power: \( P = h \nu \Phi \) (in Watts)
  where \( \Phi \) is number of emitted photons per unit time.
- \( \Phi = \eta \, I/e \) (\( I \) in Amperes)
- \( \eta = \# \text{ emitted photons per sec.} / \# \text{ injected electrons per sec.} \)
- \( \eta \) (quantum efficiency) accounts for the fact that
  - Only a fraction of the injected electrons are converted into photons (internal quantum efficiency).
  - Only a tiny fraction of the generated photons emerge from the device. Photons are re-absorbed by the substrate or are reflected at the semiconductor surface.
- \( P = h \nu \eta \, I/e = 1.24 \, \eta \, I/\lambda \) (\( \lambda \) in \( \mu \)m, \( I \) in Amperes and \( P \) in Watts)
- Wallplug efficiency (power conversion efficiency): the ratio of the emitted optical power to the input electrical power.
Efficiency of blue, green, red and “white” LEDs

Fig. 4. Historical evolution of commercial LEDs. From [42]. PC-White stands for phosphor converted white light, DH stands for double heterostructure. The wallplug efficiency is the ratio between emitted light power and supplied electrical power.

Another measure of LED efficiency

- **Luminous efficacy** = luminous flux / radiant flux (total emitted power).
- The *luminous flux* is the power emitted in the visible range, but **weighted by the eye's response to light**: the visible power is *weighted* by the *luminosity function* that represents the eye's response to different wavelengths. Non-visible emission does not count.

Different luminosity functions apply under different lighting conditions (photopic in bright conditions, mesotopic and scotopic under low lighting conditions).

*Source: Wikipedia*
LED structures

Surface-emitting

Edge-emitting

Carrier injection

Light emission

(carrier injection and light emission)

(semiconductor amplifiers and diode lasers are also fabricated with these types of structures).
LED optical spectrum

Rate of spontaneous emission: 
\[ r_{sp}(\nu) = D (\nu - E_g)^{1/2} \exp\left(-\frac{\nu - E_g}{k_B T}\right), \quad \nu \geq E_g \]

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

Density of states

Probability of occupancy (Boltzmann)

Peak frequency 
\[ \nu_p = E_g + \frac{k_B T}{2} \]

Spectral width (FWHM) 
\[ \Delta \nu \approx \frac{1.8 k_B T}{\hbar} \]

\[ k_B = 8.6 \times 10^{-5} \text{ eV/K} \]

\[ \hbar = 4.13 \times 10^{-15} \text{ eV s} \]

\[ \Delta \nu \approx 11 \text{ THz} \quad (1 \text{ THz} = 10^{12} \text{ Hz}) \]
when \( T = 300 \text{ K} \)
LED linewidth vs. wavelength

\[ \Delta \lambda \approx 1.45 \lambda_p^2 k_B T \]

(when \( k_B T \) in eV and \( \lambda_p \) –peak emission- in \( \mu \text{m} \))

\[ \lambda_p = 1 \ \mu \text{m at } T = 300 \ K: \Delta \lambda \approx 37 \ \text{nm} \]
Summary

- The operation principle of LEDs is spontaneous recombination: electro-luminescence.
- LEDs emit non-coherent light.
- No threshold: the emitted optical power increases linearly with the injected current.
- LI curve saturates at high pump current (efficiency drop due to Auger effect).
- The LED efficiency is measured by:
  - Wall-plug efficiency (emitted optical power / input electric power),
  - Luminous efficacy (visible optical power, weighted by the eye's response to light / total optical power).
Outline

- Introduction
- Light-matter interactions in semiconductor materials
- LEDs
- Semiconductor optical amplifiers (SOAs)
- Diode lasers

Which is the operation principle of a SOA?
How to estimate the gain, bandwidth and threshold?
How to lower the threshold and how to increase the gain?
SOA operation principle is based on **stimulated emission**

- A SOA **coherently** amplifies an input optical signal, without converting it into an electrical signal.
- An optical amplifier is a laser without an optical cavity.
- Large numbers of electrons and holes are needed to overcome absorption.
- **How to achieve a high enough carrier concentration?**
- **Two mechanisms for generating electrons and holes:**
  - Injecting electrons (same as LEDs, **Electrical pump**).
  - Injecting high energy photons (>\(E_g\), **Optical pump**).
Optical amplifiers are used as optical repeaters in the long distance fiber-optic cables that carry internet traffic.

**Main types:**
- Semiconductor optical amplifiers
- Fiber amplifiers
  - The **erbium-doped fiber amplifier** (EDFA) is the most used fiber amplifier because its amplification window includes the conventional C-band (1525-1565 nm) and the long L-band (1565-1610 nm) of optical fibers. It is optically pumped, typically with a diode laser.
  - **Raman amplifier**: based on Raman scattering of incoming light with “phonons” in the lattice of the gain medium, that produces photons that are fully coherent with the incoming photons.

An isolator or an AR-coating is usually placed at the output of the amplifier to prevent reflections that can interfere with the operation.
SOAs are used for up to 40 km transmission among data centers, and between mobile phone base stations and data centers.

*Light source for communication: 1.3 μm band

EDFAs are used for long-distance links

**THE SUBMARINE WEB**

Much of the world’s Internet traffic passes under the oceans, through fibre-optic cables that can run along the sea bed for thousands of kilometres. Companies are constantly laying more and better cables.

Opened in June 2016 by Google and five Asian firms, this is currently the highest-capacity submarine cable in service.

When completed in October 2017, this Facebook- and Microsoft-owned cable will carry data across the Atlantic at almost triple FASTER’s capacity.

Completed in late 2000, this is the longest submarine cable. It has 39 landing points and 92 investors.

Relation between the injected current and the carrier concentration

\[ J = \frac{i}{(w \ L)} \]

Pump current density (Ampere per unit area)
\[ i = \text{electric current (Ampere)} \]

\[ R_e = \frac{(i/e)/(w \ L \ d)}{J/(e \ d)} \]

Injection rate (number of injected electrons per unit time and unit volume)
\( d \) is the thickness of the “depletion layer”

Steady-state injection condition:
recombination rate \( R = \text{injection rate} \ R_e \)

\[ \frac{dN}{dt} = -R = -\frac{N}{\tau_N} \]
(\( \tau_N \): carrier lifetime)

\[ \frac{1}{\tau_N} \times N = \frac{(i/e)/(w \ d \ L)}{J/(ed)} \Rightarrow \]

\[ J = \frac{e \ d \ N}{\tau_N} \]
Amplifier threshold condition: transparency

Transparency condition: No gain.
1 incoming photon produces 1 outgoing photon.

\[ J = \frac{e \cdot d \cdot N}{\tau_N} \quad \Rightarrow \quad J_0 = \frac{e \cdot d \cdot N_0}{\tau_N} \]

\( J_0 \) = current density needed to reach transparency.
\( N_0 \) = carrier concentration at transparency.
Exercise

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

\[ \tau_N = 1.25 \, \text{ns}, \quad N_0 = 1.25 \times 10^{18} \, \text{cm}^{-3}, \quad w = 10 \, \mu\text{m}, \quad L = 200 \, \mu\text{m}, \quad d = 2 \, \mu\text{m}. \]

- Calculate the transparency current density.
- Calculate the injection current required to produce this current density.

\[ J_0 = 3.2 \times 10^4 \, \text{A/cm}^2 \quad i = 0.7 \, \text{A} \]
Can we lower the amplifier threshold?

\[ J_0 = e \frac{d N_0}{\tau_N} \]

- \( N_0 \) and \( \tau_N \) are determined by the material.
- \( J_0 \) is proportional to \( d \) (thickness of the “depletion layer”).
- Reducing \( d \) will reduce the threshold.
- However, carrier diffusion prevents from confining electrons and holes in too small regions (their diffusion lengths are several \( \mu m \)).
- Can we confine the carriers to a region whose thickness is smaller than the carrier diffusion length?
- Yes. By using different semiconductor materials (“hetero-structures”).
- The second generation of diode lasers were hetero-structures.
Double Hetero-structures (DH): two main advantages

1) Improved electron and hole confinement in the “active layer” because the semiconductors with different band-gaps

2) Improved photon confinement: the “active layer” acts as a waveguide because the semiconductors have different refractive index
Example of a Double Hetero-structure

- **Improved photon confinement** due to the larger index of refraction \((n = 3.6)\) of GaAS compared to the \(p\)- and \(n\)-cladding layers \((n = 3.4)\).

- **Improved carrier confinement** due to the smaller band gap \((E_g \approx 1.5 \text{ eV})\) of GaAs compared to the \(p\)- and \(n\)-cladding layers \((E_g \approx 1.8 \text{ eV})\).
The adoption of DH technology significantly decreased the 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**).
Development of DH technology

- Trying to find the “ideal couple” was difficult and the patent for the DH laser was initially viewed as a “paper” patent.

- Which couple? Ga As popular because
  - “direct” band structure
  - wide energy gap
  - effective radiative recombination
  - high carrier mobility

- Good candidate for “partner” material (close value of the lattice constant): AlAs.

- But AlAs is chemically unstable and decompose in moist air.

- But AlGaAs turned out to be stable and suitable for durable heterostructures.

- AlGaAs heterostructures were used for RT diode lasers and became the basis for modern optoelectronics.
The 2000 Nobel Prize in Physics

The improved photon, electron and hole confinement in DH structures allowed for cw RT lasing, which enabled the development of technologies with huge socio-economic impacts.

“For developing semiconductor heterostructures used in high-speed- and opto-electronics”

“For his part in the invention of the integrated circuit”
Early 1980s: moving the DH technology one step further to quantum wells (QWs)

- A QW is a DH structure whose thickness is of a few nanometers.
- It is comparable to the de Broglie wavelength ($\lambda=h/p$) of the carriers (electrons and holes).
- Within the quantum well, there are discrete energy states that carriers can have.

Example of a QW structure

Density of states in a quantum well

- In a QW the energy-momentum relation of a bulk material does not apply.
- In a QW the carriers are confined in one direction (x) but in the ⊥ y-z plane they behave as in a bulk semiconductor.
In a QW the transparency current density is several times smaller than comparable DH. However, the thin layer of the QW is way too small to effectively confine the light. Solution: periodic hetero-structure made of alternating materials with different band-gaps (“superlattice”).
Multiple Quantum Wells (MQWs)

- Alternating layers of “active” (narrow band gap) material with barrier (high band gap) material.
- The QWs are “uncoupled”: the barriers have to avoid the coupling of adjacent wave functions (no electron tunneling).
- Varying the material composition of the QW or barrier, the layer or barrier thickness, or the number of QWs can change the emission characteristics of the MQW.

Advantages:
- Reduced threshold current
- Reduced carrier loss
- Reduced temperature sensitivity
- Increased efficiency
- Higher output power

Drawback: increased fabrication cost.

Modern semiconductor light sources are based on MQWs.
Fabrication techniques

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

- **Metalorganic vapour phase epitaxy (MOVPE)** uses chemical reactions to grow crystalline layers.
- **Molecular-beam epitaxy (MBE)** uses molecular beams of the constituent elements in a high-vacuum environment and is based on controlling physical deposition rates.
- **Liquid-phase epitaxy (LPE)** uses the cooling of a saturated solution containing the constituents in contact with the substrate (but layers are thick).

Advances in these techniques were crucial for lowering fabrication costs.
The compositions and dopings of the layers are determined by manipulating the arrival rates of the molecules and the temperature of the substrate surface.
Impact of QWs on the creation of the Internet

- Long-wavelength QW lasers are nowadays the light sources used for long-distance fiber optic communications.
- Early work on QW lasers focused on GaAs wells bounded by AlGaAs walls, but wavelengths transmitted by optical fibers are best achieved with indium phosphide (InP) walls with indium gallium arsenide phosphide (GaInAsP) based wells.
- The central practical issue of light sources buried in cables is their lifetimes to burn-out. The average burn-out time of early long-wavelength QW lasers was less than one second.
- Success was achieved in the early 1990s by Joanna (Joka) Maria Vandenberg, with quality control of QW laser production by MOVPE, using high-resolution X rays.
- Her quality control produced long-wavelength lasers with median burn-out times longer than 25 years.

https://en.wikipedia.org/wiki/Joanna_(Joka)_Maria_Vandenberg
The lower the dimension is, the higher and narrower the gain is.

Quantum dots (QDs): discrete electronic energy states $\Rightarrow$ atom-like transitions.

Asada et al, IEEE JQE 1986
How to make quantum dots?

- Through the Asaro-Tiller-Grinfeld (ATG) 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 allows to fabricate self-assembled QDs.
Evolution of the threshold of a diode laser

State of the art: almost threshold-less lasers (more latter -nanolasers)

SPSL: short-period super-lattices

Source: Z. Alferov IEEE JSTQE 2000
Summary (1/2)

- An optical amplifier amplifies optical signals without converting them to electric signals.
- Semiconductor optical amplifiers are based on stimulated e/h recombination.
- SOAs can be electrically or optically pumped; in the latter case, photons with $h\nu > E_g$ are used to generate pairs of electrons and holes.
- The amplifier threshold is at transparency: the carrier population is large enough such that stimulated emission overcomes absorption, and one input photon produces one output photon.
- The pump current needed to achieve transparency is proportional to the width of the “active region” (the “depletion layer” of homo-structures).
Summary (2/2)

- Double hetero-structures (composed by semiconductor materials with different bandgaps) strongly improve both, carrier and photon confinement.
- The development of DH allowed diode lasers that emitted a cw output at RT.
- QWs are DHs with a very thin “active” region.
- QWs and Qdots have higher gain than “bulk” materials.
- The small thickness of a QW does not allow a good confinement of the photons ⇒ MQWs. The active region of modern semiconductor light sources is composed by MQWs.
Outline

- Introduction
- Light-matter interactions in semiconductor materials
- Light Emitting Diodes (LEDs)
- Semiconductor optical amplifiers
- **Semiconductor (diode) lasers**
  - Characteristics (LI curve, optical spectrum, thermal effects)
  - Types of semiconductor lasers
Semiconductor laser = semiconductor material (amplifier) + optical cavity

The **simplest** cavity is the Fabry-Perot cavity formed by the parallel cleaved facets of the semiconductor material.

This structure is known as Edge-Emitting laser (EEL)

**Diode lasers:** semiconductor lasers that are **electrically pumped**.

Fabrication steps:
- epitaxial growth,
- wafer processing,
- facet treatment,
- packaging.
Reminder: diode lasers are a big part of the laser market.

QCLs are semiconductor lasers but are not diode lasers.

Source: Thorlabs
In the lab, laser diodes need temperature and current controllers.

Current controller

Temp. controller

Light output power vs. electric pump current (LI curve)

![Graph showing light output power vs. pump current for a laser diode. The graph illustrates stimulated and spontaneous emission.](image)

Figure 2.2: Output power vs. pump current of a laser diode. When the gain is larger than the losses the system begins to lase, this happens at the threshold, indicated with an arrow (27.8 mA in this case). The laser used is a 675 nm AlGaInP semiconductor laser (Hitachi Laser Diode HL6724MG).

*Source: A. Aragoneses PhD Thesis 2014, UPC.*
Diode laser – LED comparison

Diode laser

Threshold current

LED

Note the different scales
Laser threshold

\[ i = w L J \] (J current density)

**J = e d N/\tau_N**

\[ J_0 = e d N_0/\tau_N \] (transparency condition)

\[ 1/\tau_N = 1/\tau_r + 1/\tau_{nr} \]

Linear approx. of the gain per unit time: \( G(N) = a \) \( (N-N_0) \)

Loss per unit time: \( v_g (\alpha_{mirror} + \alpha_{int}) = 1/\tau_p \)

(\( \tau_p \): Photon lifetime in the cavity, before is “lost”)

**Threshold condition: gain = losses**

\[ a \ (N_{th}-N_0) = 1/\tau_p \implies N_{th} = N_0 + 1/(\tau_p a) \]

\[ J_{th} = e d N_{th}/\tau_N = e d [N_0 + 1/(\tau_p a)]/\tau_N \implies J_{th} = J_0 + e d / (\tau_N \tau_p a) \]
At threshold the carrier injection rate balances the rates of non-radiative + radiative (spontaneous emission) recombinatinon

Carrier injection rate* = carrier recombination rate

\[ J/(e d) = N/\tau_N = N/\tau_{nr} + N/\tau_r \]

**Carrier radiative** recombination rate = Photon emission rate

\[ N/\tau_r = (\text{Gain} - \text{losses}) S + R_{sp} \]

Stimulated emission and absorption rates

\[ S: \text{Photon density} \]

Spontaneous emission rate

At threshold: Gain = Losses \( \Rightarrow R_{sp} = N_{th}/\tau_r \)

\[ J_{th} /(e d) = N_{th}/\tau_{nr} + N_{th}/\tau_r \] (as seen in the previous slide)

\* \( R_e \) = number of injected electrons per unit time and unit volume
To further reduce the threshold: lateral confinement

Gain guided (carrier induced $\Delta n$)

At higher currents thermal effects lead to saturation (not shown)
How low can the threshold of a semiconductor laser be?

- It is possible to control both, photon states and atom states by placing an atom in a quantum optical cavity ("cavity Quantum Electrodynamics – cavity QED")

- When the electronic transition is on resonance with the cavity mode, the spontaneous emission rate can increase (or decrease) dramatically.

- Example: atom with wavelength $\lambda$ placed in a cavity of length $d < \lambda/2$: no allowed emission modes $\Rightarrow$ spontaneous emission inhibited.

- But spontaneous emission can be enhanced if the atom is placed in a cavity of small volume and high Q factor ($Q = 2\pi \times$ energy stored / energy lost per cycle $= 2\pi v_0 \tau_p$).

- This is known as the “Purcell effect” that enables ultra-low threshold lasers. It can also increase the modulation speed.
Spontaneous emission enhancement factor

- $\beta$: fraction of total spontaneous emission that is coupled to the lasing mode.
- If the cavity length is $L=100 \, \mu\text{m}$: $10^{-5}$
- For a cavity of a few microns with 3D confinement: $\beta \to 1$

LI curve (log-log scale)
Light – injected current curve (LI curve)

- Emitted optical power: \( P = h \nu \Phi \) (in Watts)
  \( \Phi \) : flux of emitted photons (photons per unit time).

- \( \Phi = \eta (I-I_{th})/e \)  (\( I, I_{th} \) in amperes)
  \( \eta \) : quantum efficiency. It accounts for the fact that only a fraction of the electron-hole recombinations are radiative (internal quantum efficiency) + only part of the emitted photons emerge from the device.

\[ P = 1.24 \eta (I-I_{th})/\lambda \]

(\( \lambda \) in \( \mu m \), \( I \) in Amperes, \( P \) in Watts; for a LED \( I_{th}=0 \))

Example:

- \( I_{th} = 20 \) mA
- \( \lambda = 1.3 \) \( \mu m \) (InGaAsP)
- \( \eta = (\lambda /1.24) P/(I-I_{th}) \)
- \[ = (1.3/1.24) \times 20/(80-20) \approx 35\% \]
Wall-plug efficiency (also known as power conversion efficiency)

- Ratio of optical power to electrical power, $WPE = P / IV$
- $P = (h \nu / e) \eta (I - I_{th})$
- $V = V_k + R_d I$
  
  $V_k$ is the kink voltage (related to the separation of quasi-Fermi energies)
  
  $R_d = dV/dI$ is the differential resistance

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

  $$I = I_{th} \cdot \left(1 + \sqrt{1 + \xi}\right) \quad \text{with} \quad \xi = \frac{V_k}{I_{th} R_d}$$
Emission characteristics: how many modes?

The semiconductor gain spectrum is broad
\[ \Rightarrow \text{supports many longitudinal modes.} \]

\[ \nu_q = q \frac{c}{(2nL)} \]
\[ \Delta \nu = \frac{c}{(2nL)} \]
\[ \Delta \lambda = \frac{(\lambda_0)^2}{(2nL)} \]

(free-space wavelength spacing)

\[ n = 3.5, L = 1 \text{ mm:} \]
\[ \Delta \lambda = 0.05 \text{ nm @ 635 nm} \]
\[ \Delta \lambda = 0.3 \text{ nm @ 1550 nm} \]
As in any laser, in a diode laser the gain bandwidth and the cavity determine the optical spectrum.

Range of frequencies where photons are amplified, determined by the gain of the laser medium.

\[ \nu_q = \frac{c}{2nL} \]

The laser linewidth, \( \Delta \nu \), is the spectral width.

Spectrum of a helium–neon laser. The actual linewidth is much narrower than shown; the resolution is limited by the measuring apparatus.
The optical spectrum depends on the temperature and on the design of the cavity

- In a semiconductor the gain and the refractive index depend on the temperature.

- It is often possible to adjust the operation conditions (the injection current, $I$, and $T$) for single-mode operation, but it can be achieved over a limited $I$ and $T$ range.
An example from our lab, when the pump current increases while the laser temperature is kept constant.

Figure 2.4: Normalized optical spectrum of a semiconductor laser of nominal wavelength of 675 nm (Hitachi Laser Diode HL6724MG) at three pump currents: (a) 29.10 mA, (b) 29.70 mA, and (c) 30.30 mA.

Thermal properties: wavelength tuning (red shift), continuous or sudden jump

Single-mode laser

Multi-mode: Mode hopping

\[ \lambda_p (\text{nm}) \]

\[ P_o = 3 \text{mW} \]

\[ P_o = 7 \text{mW} \]

\[ \lambda_p (\text{nm}) \]

\[ \text{Case temperature } T_c \left( ^\circ \text{C} \right) \]

\[ \approx 0.27 \text{ nm/C} \]
Why thermal shift?

- With increasing current, the semiconductor medium heats up (Joule heating).

- Temperature affects:
  - the gain (the peak and the width)
  - the refractive index

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

- The temperature modifies the refractive index, \( n \), which in turn modifies the cavity resonances.

\[ \nu_q = \frac{q \cdot c}{2nL} \]
Why the red-shift?

- Near threshold the spontaneous emission is “colored” by the resonances of the laser cavity.
- $I$ increases $\Rightarrow$ $T$ increases $\Rightarrow$ the refractive index, $n$, increases $\Rightarrow$ increases the modal wavelengths (redshift).
- The peak of the gain spectrum also redshifts.
- The redshift of the gain is larger than the redshift of the modes $\Rightarrow$ eventually switch to another mode at longer wavelength with higher gain.

A limit for the wavelength emitted by conventional semiconductor lasers

- Conventional “inter-band” semiconductor lasers operate on “band-to-band” electron/hole radiative transitions: when electrons in the conduction band decay to the valence band, the energy is transferred to a photon.

- There is a limit of the emitted wavelength because for long wavelengths, the released (small) energy, $h\nu$, is re-absorbed by another carrier and eventually transferred to heat.

- Thus, conventional “inter-band” lasers emit up to 2-3 $\mu$m (NIR).

Solution: **intra-band** transitions, i.e., transition between 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 almost 20 years latter, in 2002
Quantum Cascade Laser (QCL) operating principle

- Electrons flow through series of quantum wells.
- Emitting a photon each time.
- No recombination of electrons and holes (a QCL is not a diode laser)
- One electron generates many photons sequentially.
- The characteristics of the QWs determine the emission wavelength, that is in the mid- to far-infrared (3 μm to THz)

Types of diode lasers

- Emission:
  - Single-mode (low power)
  - Multi-mode (high power)

- Cavity:
  - Fabry–Perot: two parallel mirrors
    - Edge emitting
    - Vertical cavity
  - Others (ring, disk, to be discussed in the next class)
Single-mode lasers

- Single-mode emission is crucial for fiber-optic communication systems, for optical sensors, and for applications that require high beam quality.
- Single-mode emission can be achieved by using a **mode-selective cavity**:
  - An *external* reflector (External-Cavity Laser)
  - An integrated *Bragg-Grating* (BG) mirror that has peak reflectivity for a specific frequency (the Bragg-frequency) via coherent addition of distributed reflections.
    - Distributed Feedback (DFB) laser
    - Distributed Bragg Reflector (DBR) laser
    - Vertical Cavity Surface Emitting Laser (VCSEL)
Anti-reflective (AR) coating and Bragg grating

At normal incidence, no reflected ray if

\[ h = \frac{\lambda}{4} \quad \text{and} \quad n_l^2 = n_0 n_s \]

Maximum constructive interference when

\[ 2d \sin \theta = n\lambda \]

where \( n \) is a positive integer.

External-cavity Laser: an external mirror provides optical feedback

- One facet of the laser has an anti-reflection (AR) coating and an output coupler mirror extends the optical cavity.
- Optical feedback lowers the threshold and can decrease the emission linewidth $\Delta \nu$.
- By tuning $L$ and $R_{\text{ext}}$ single-mode emission can be obtained, in a mode of the compound cavity, $l+L$.
- However, the residual reflection from the AR-coated facet can lead to line broadening and the emission of a chaotic output.
Effect of optical feedback on the LI curve

The amount of optical feedback is usually quantified by the % of reduction of the threshold pump current.

Why “optical feedback” lowers the threshold and can decrease the linewidth?

- Diode lasers have a much larger linewidth, $\Delta \nu$, than other lasers: a typical diode laser linewidth is 50-100 MHz, whereas the linewidth of a typical HeNe laser (2 mW output power) is 100 kHz.

- Why large $\Delta \nu$? In a semiconductor the refractive index ($n$) depends on the carrier density ($N$). Fluctuations in the photon density, due to spontaneous emission, produce fluctuations in $N$ that modify $n$ (more latter, in “Models”).

- Schawlow-Townes-Henry linewidth formula (Schawlow-Townes: $\Delta \nu \sim 1/P_{\text{out}}$).

\[
\Delta \nu = \frac{h \nu v_g^2 (\alpha_i + \alpha_m) \alpha_m n_{sp}}{8 \pi P_{\text{out}}} \left(1 + \alpha_H^2\right)
\]

$\alpha_H =$ \text{\textalpha-factor}

Important parameter!

Typical MQWs: 3-4

- Increasing $L$ decreases $\alpha_m$, $\Rightarrow$ reduces $\Delta \nu$ and $g_{th}$.

But optical feedback can also produce “coherence collapse”: an enhancement of the bandwidth of the optical spectrum.


Distributed FeedBack (DFB) Laser

- A DFB laser incorporates a grating in one of the cladding layers surrounding the active layer.
- The grating selects the wavelength: the forwards and backwards propagating beams interfere constructively if:

\[ \lambda = \lambda_B = 2 <n_{\text{eff}} > \Lambda \]

where \(<n_{\text{eff}} >\) is the average refractive index along the z-axis.

- Because the grating is distributed along all the gain region, the grating and gain region experience similar conditions when the laser is tuned with current and temperature.

  \[ \Rightarrow \text{DFB exhibits a continuous tuning range (} \approx 0.2-0.5 \text{ nm/C).} \]

- But over a sufficiently large current or temperature variation, the emitted \(\lambda\) will suddenly jump to a mode with higher gain and longer \(\lambda\) (red shift).
Comparison of optical spectra

Distributed FeedBack (DFB, more latter)
Applications

- DFB lasers emitting in the lowest loss window of optical fibers (1.55μm), amplified by erbium-doped fiber amplifiers (EDFAs), are used for long distance communications.

- DFB lasers emitting in the lowest dispersion window (1.3μm) are used for shorter distances.
Distributed Bragg reflector (DBR) laser

- Incorporates a “passive” DBR mirror on one end (multiple layers of alternating materials with different refractive index).

Difference between DBR and DFB lasers

The tuning characteristics of the DBR mirror are different from those of DFB because increasing current causes a red shift of the gain and cavity modes, but the reflectivity curve of the passive grating does not change.

⇒ Blue shift to a mode with higher reflectivity, which will have higher (gain-loss).
Vertical Cavity Surface Emitting Laser (VCSEL)


(the VCSEL’s operation principles will be presented next class)
Comparison

Edge-emitting laser

Output beam

Electric “pump”

L=300-500 μm

The cleaved surfaces act as reflectors.

Vertical-cavity surface-emitting laser

Output beam

Electric “pump”

L=1-10 μm (tiny!)
(the width of the QWs region)

Because of small L, highly reflective mirrors are needed.

Comparison of the transverse modes

The circular profile allows easy coupling to an optical fiber.

But single-transverse mode emission is limited to low output power (few mW).

Fundamental transverse mode operation can be achieved by carefully matching the area of the optical mode to the area of the “active” region (where there is gain due to the presence of electrons and holes).
Summary

- Diode lasers are electrically pumped semiconductor lasers.
- The active region is usually composed by several QWs.
- Threshold condition: the gain balances the round-trip loss.
- Assuming a linear approximation for gain, $G = a(N - N_0)$, then $N_{th} = N_0 + 1/(\tau_p a)$.
- Under steady state conditions: rate of injected carriers = rate of recombination, $J/(e d) = N/\tau_{nr} + N/\tau_r$
- Single-mode or multi-mode emission.
- The emitted wavelength can be tuned by varying the pump current or the temperature ($\approx 0.3-0.5$ nm/C).
- Diode lasers have edge-emitting or vertical cavity geometries.
- Different III-V semiconductor materials cover a wide range of wavelengths.
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