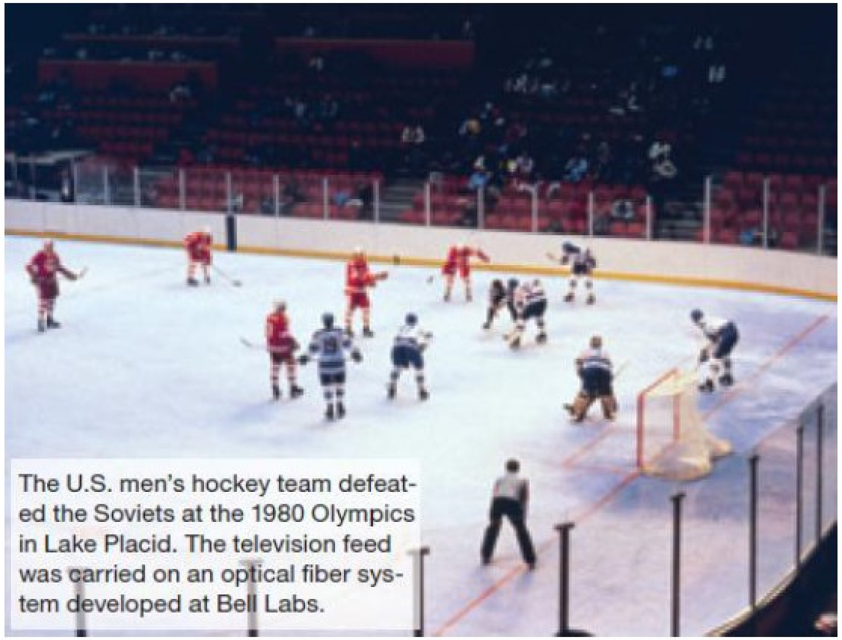
Part I: Semiconductor Lasers

Lecture 4

- Semiconductor laser basics

SCL history

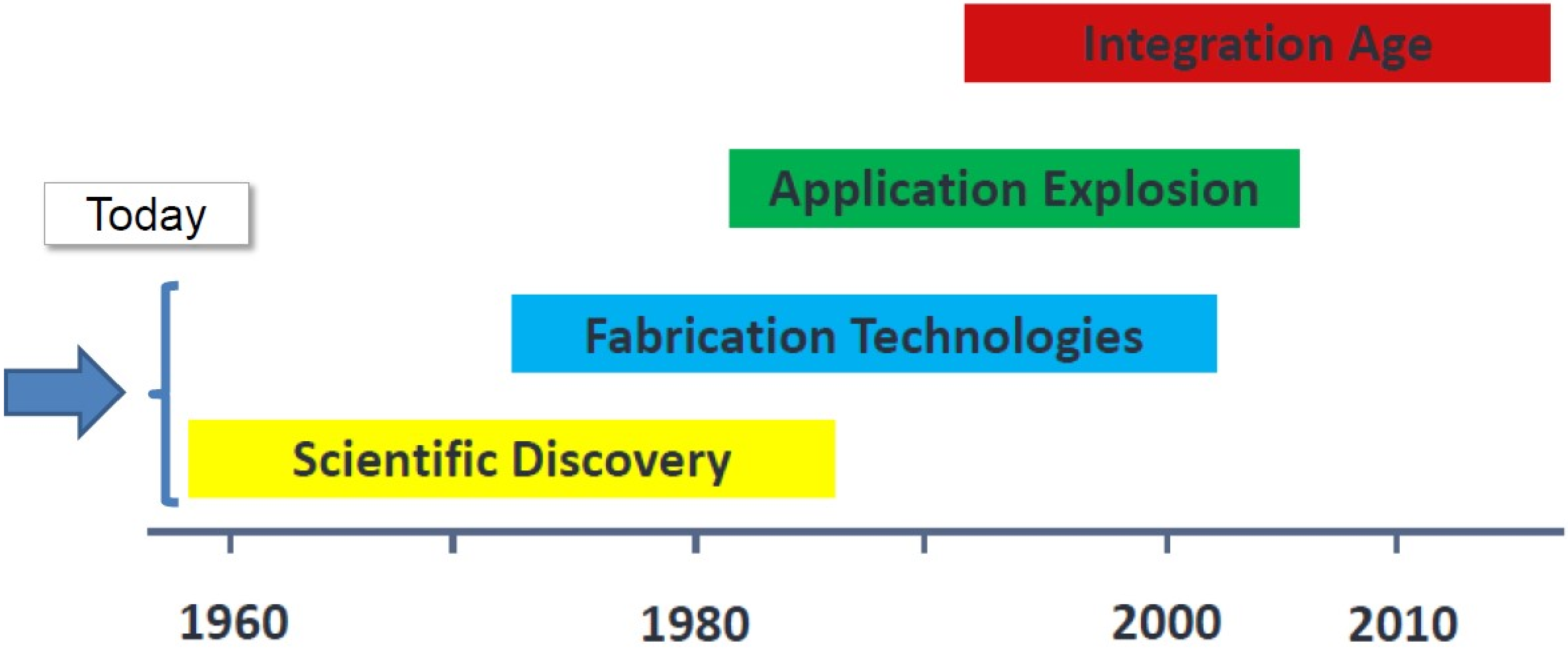
- First demonstration: **1962** (pulsed operation, cryogenic temperatures).
- cw RT emission: **1970**
- In the 60' & 70': SCLs where "**a solution looking for a problem**".
- The first practical application: February **1980**, an optical fiber system was used to **broadcast TV** (Winter Olympics, Lake Placid, US).



The U.S. men's hockey team defeated the Soviets at the 1980 Olympics in Lake Placid. The television feed was carried on an optical fiber system developed at Bell Labs.

Source: Optics & Photonics News May 2012

Laser diode evolution



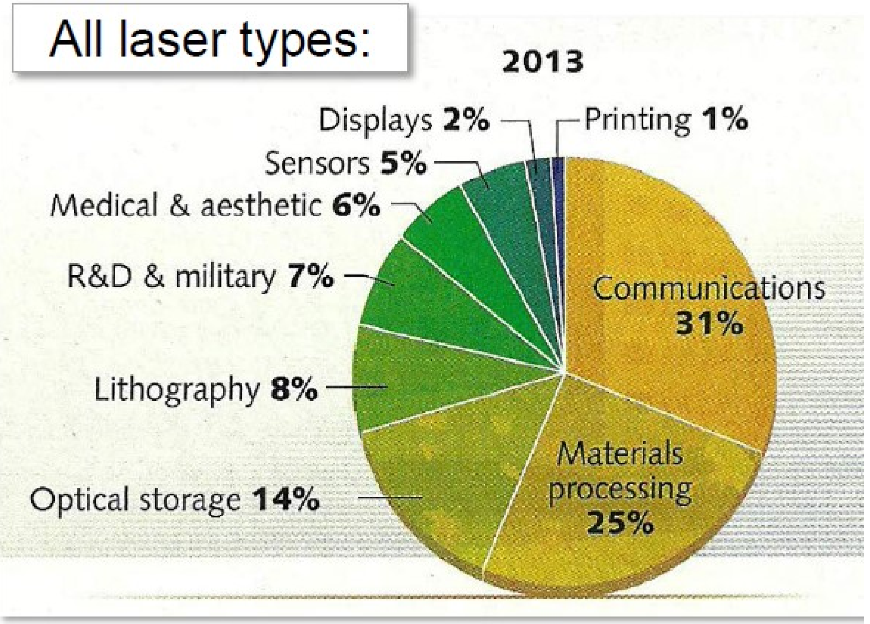
上海科技大学
ShanghaiTech University

Main applications

- Optical fiber communications
- Optical storage

No diode laser

⇒ No internet!



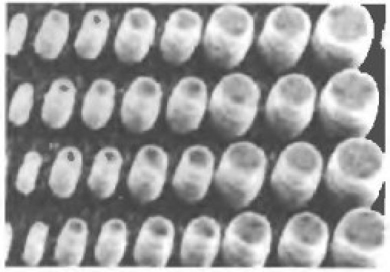
- But diode lasers are also widely used in printers, scanners, sensors, pumping of solid-state lasers, etc.
- A dramatic reduction of the fabrication price made possible these applications

The diode laser in a computer mouse costs about 10 US cents

上海科技大学 ShanghaiTech University

For telecom & IT applications

- Diode lasers can be **modulated at high speeds**: fast response to high-frequency information-modulated currents.
- Semiconductor materials provide a **wide range of wavelengths**. In particular, in the low-loss and low-dispersion regions of optical fibers.
- Easy integration in 1D & 2D arrays.



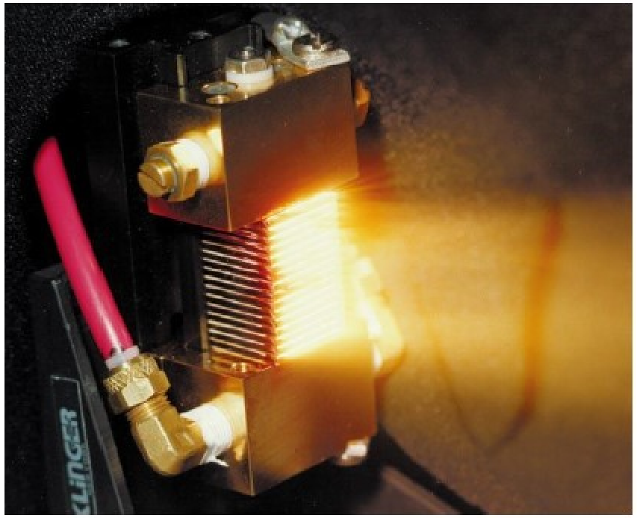
VCSELs with diameters between 1 and 5 μm. Adapted from Saleh and Teich

上海科技大学
ShanghaiTech University

For high power applications

- One laser diode produce $>$ 1 W power

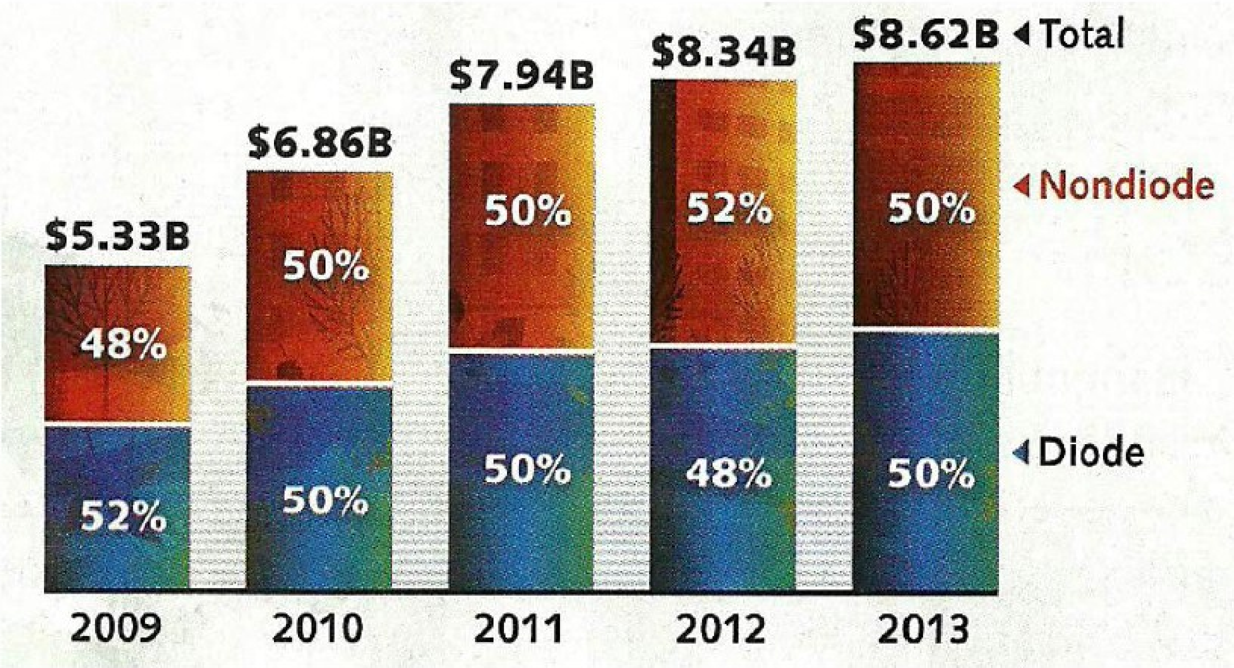
- Diode lasers are used to pump **solid-state lasers**, such as the Nd:YAG. Laser diodes are tuned to the absorption band of the crystal providing efficient pumping.
- Also used to pump **Erbium Doped Fiber Amplifiers** (EDFAs), which are crucial for the amplification of signals in long distance fiber-optic links.



Source: Wikipedia

上海科技大学 ShanghaiTech University

SCL market



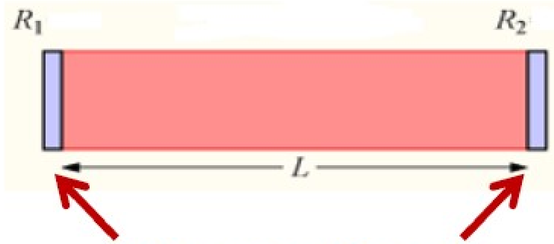
- They enable the development of key transformation technologies with **huge social impact**.

Source: Laserfocusworld.com

上海科技大学 ShanghaiTech University

Why are SCL so successful?

- The semiconductor medium has **huge gain** & do not require fragile enclosures or mirror alignment (the laser cavity is composed by the two facets of the semiconductor).
- **Low cost** fabrication because of existing semiconductor technology.



Cleaved facets

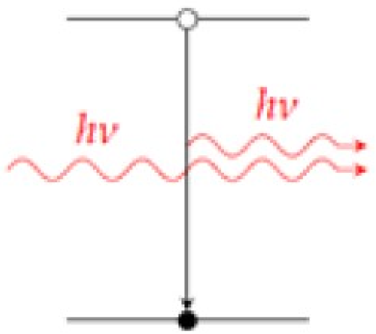
- Compared to other lasers, diode lasers are **very efficient** (nowadays 100% for the output photons with respect to the injected electrons).

- **Bright output** considering their **small size**.
- **Low threshold** current, **low energy consumption**.

上海科技大学 ShanghaiTech University

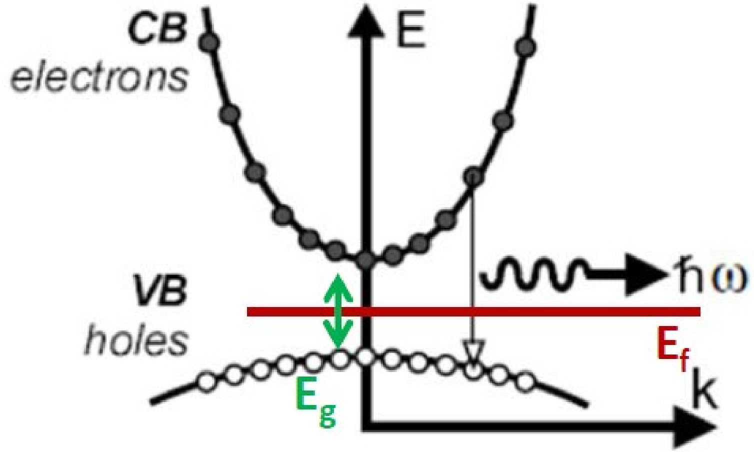
Comparison with a 2-level system

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



A particle in an excited state decays emitting a photon

In a semiconductor: electron/hole pairs & energy bands



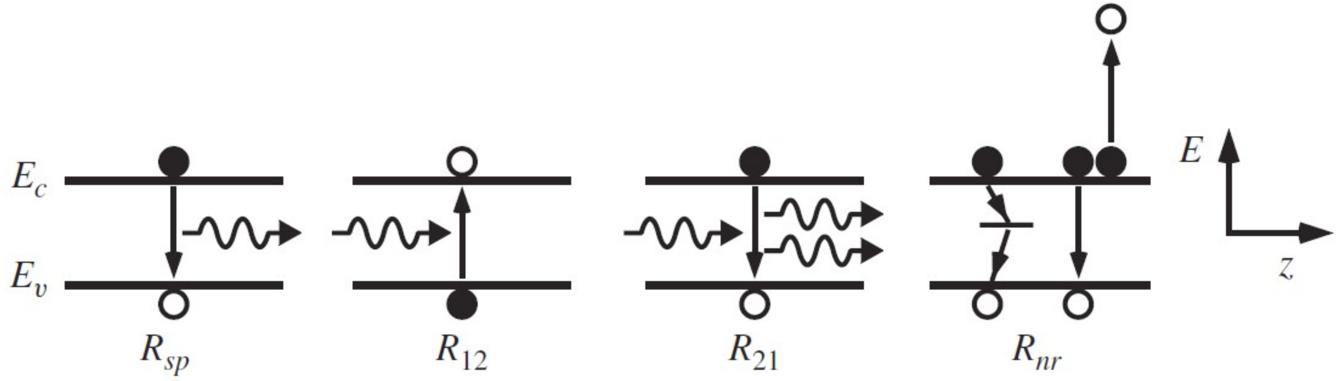
An **electron** in the CB and a **hole** in the VB recombine emitting a photon

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

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

上海科技大学 ShanghaiTech University

Electronic recombination/generation (R/G)



- Spontaneous emission, (carrier R)

Incoherent, the rate R_{sp} is proportional to N*P

- Stimulated absorption (carrier G)
- Stimulated emission, coherent (carrier R)

Coherent, the net rate (R_{21}-R_{12}) is proportional to N_P*(N-N_{tr}), R_{21}=R_{12} at transparency (Gain is zero, in contrast to the threshold, gain=loss).

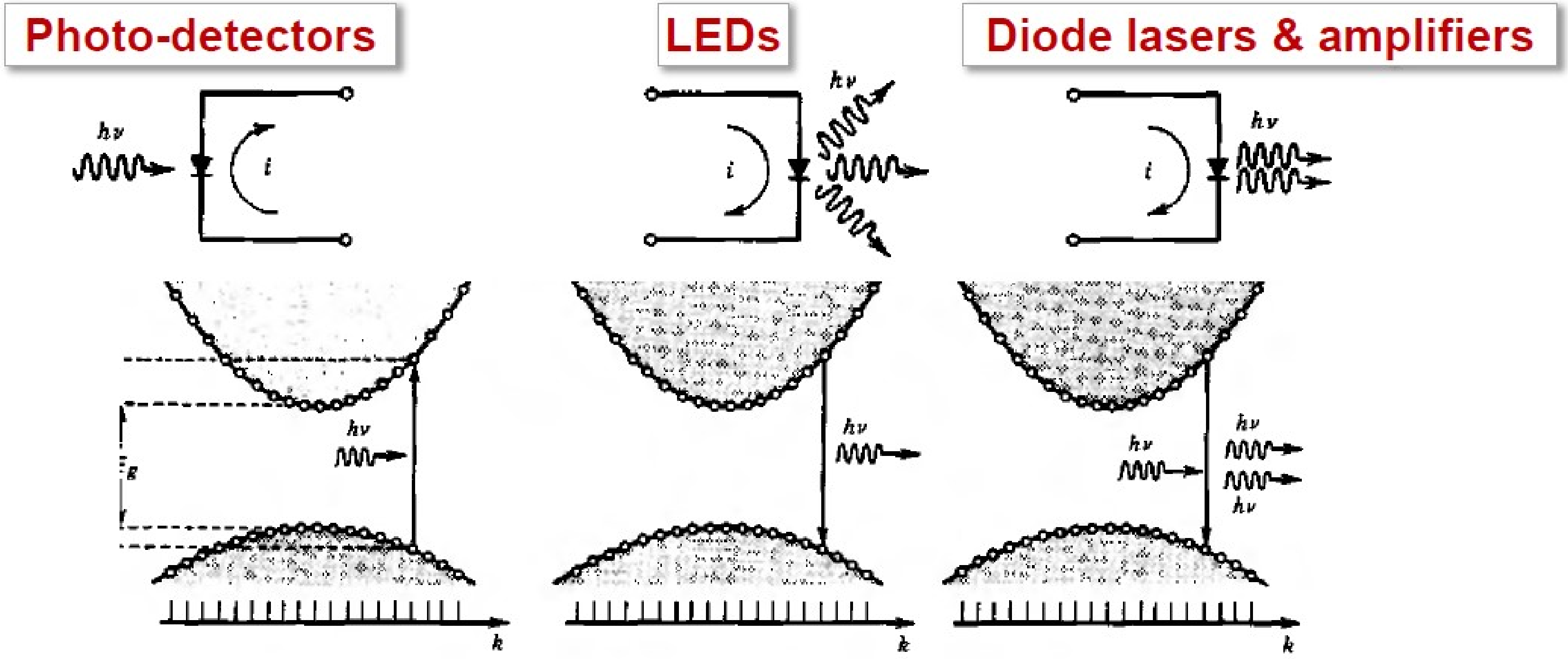
- Nonradiative carrier R

Induced by defects, surfaces, and interfaces, interact with phonon, the rate proportional to N;

Induced by Auger recombination, the energy is transferred to a third carrier, the rate proportional to N^3;

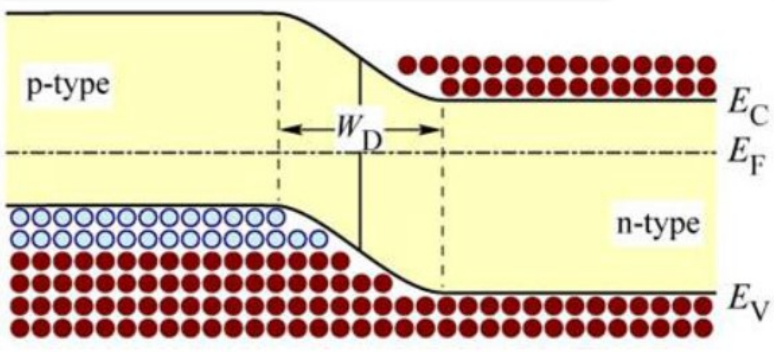
上海科技大学 ShanghaiTech University

Optical transitions

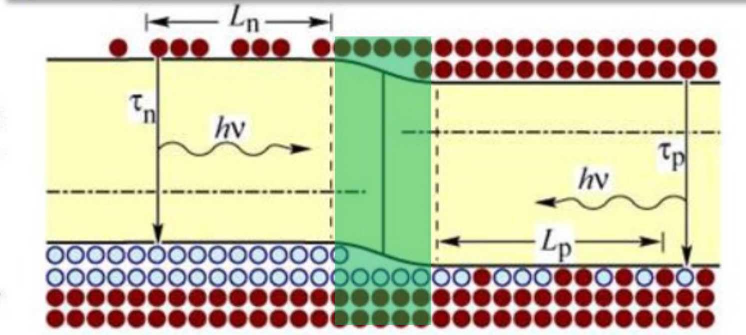


Homostructure SCL (1st generation)

p-n junction under 0 bias



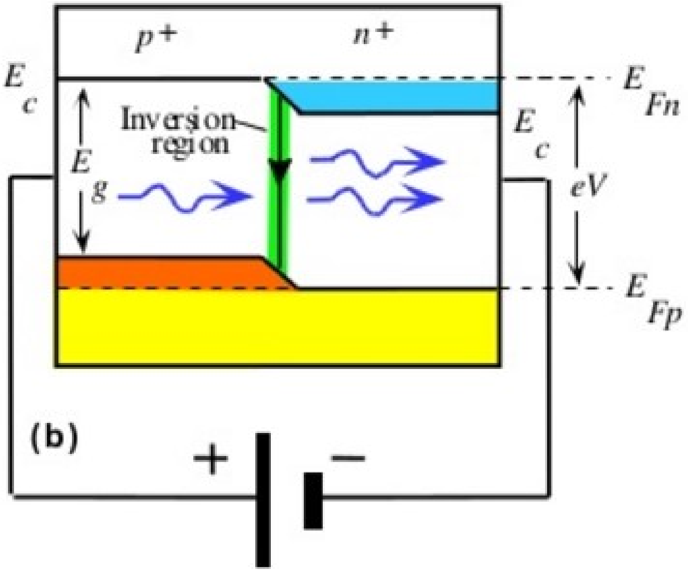
p-n junction under forward bias



- Forward bias reduces the potential barrier, and thus the electrons move to the p-doped side while holed move to the n-doped side.
- Meanwhile, there is an active region near the depletion layer that contains simultaneously holes and electrons (in the same spatial region).
- In the active region, population inversion is achieved.
- The population inversion leads to the stimulated emission.

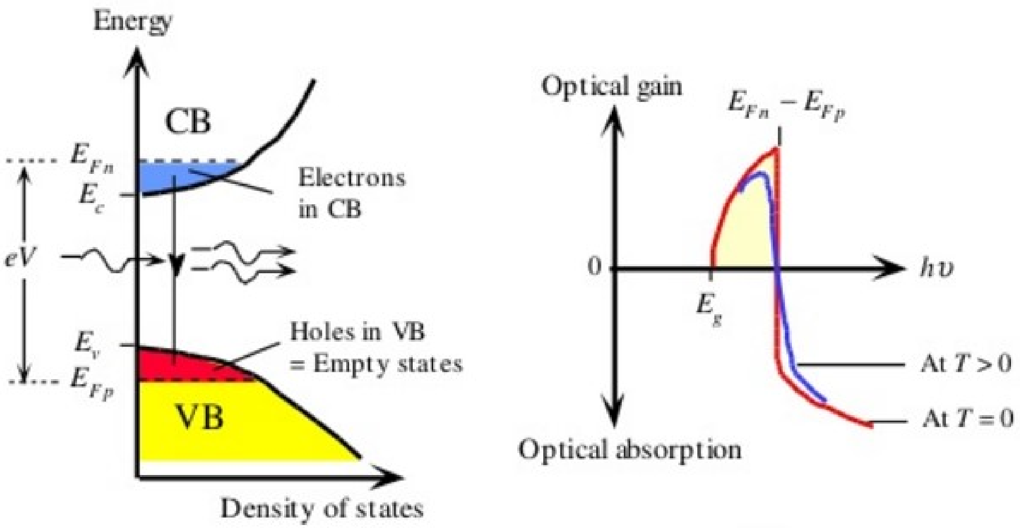
上海科技大学 ShanghaiTech University

Homostructure SCL



- The forward bias voltage is greater than the band gap $eV>E_g$.
- The quasi-Fermi levels is pulled into the conduction band and the valence band.
- The separation between E_{Fn} and E_{Fp} equals to the applied potential energy.
- The built-in potential barrier becomes almost zero.

Homostructure SCL

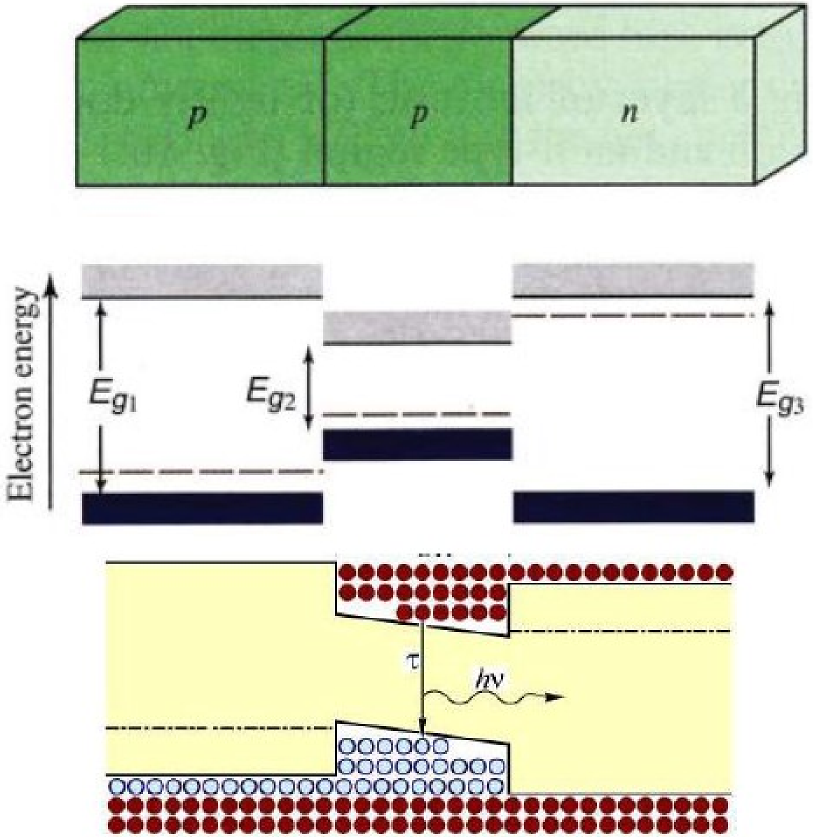


- For E_g<ΔE<E_{Fn}-E_{Fp}, the electron density in the conduction band N_c is more than that in the valence band N_v, the population inversion ΔN=N_c-N_v>0, the gain is positive.
- For ΔE=E_{Fn}-E_{Fp}, the electron density N_c=N_v, so ΔN=0, the gain is zero.
- For ΔE>E_{Fn}-E_{Fp}, the electron density N_c<N_v, so ΔN<0, the gain is negative (absorption).

上海科技大学 ShanghaiTech University

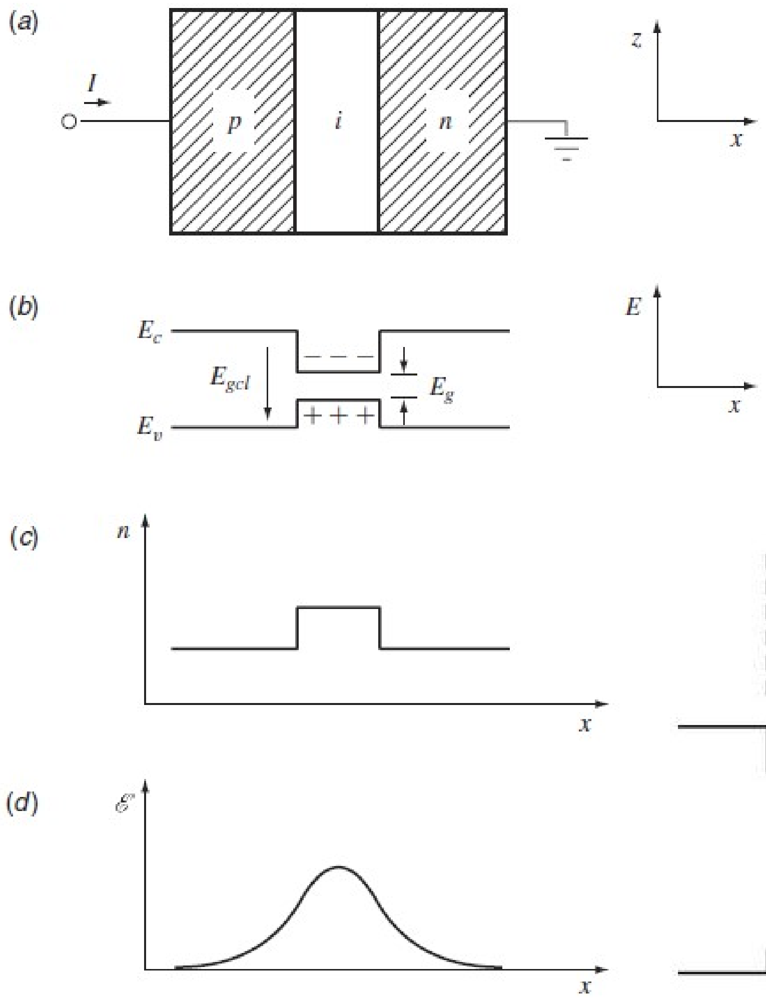
Double heterostructure SCL (2nd generation)

- The double heterostructure confines carriers in the active region, and thus improves the interaction efficiency between electrons and holes.

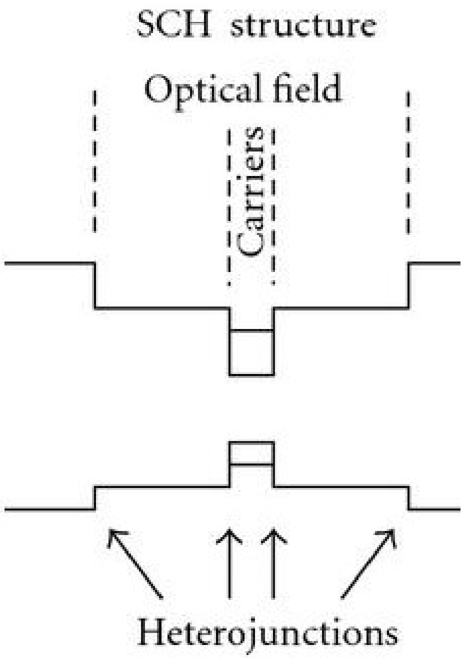


上海科技大学
ShanghaiTech University

Double heterostructure SCL



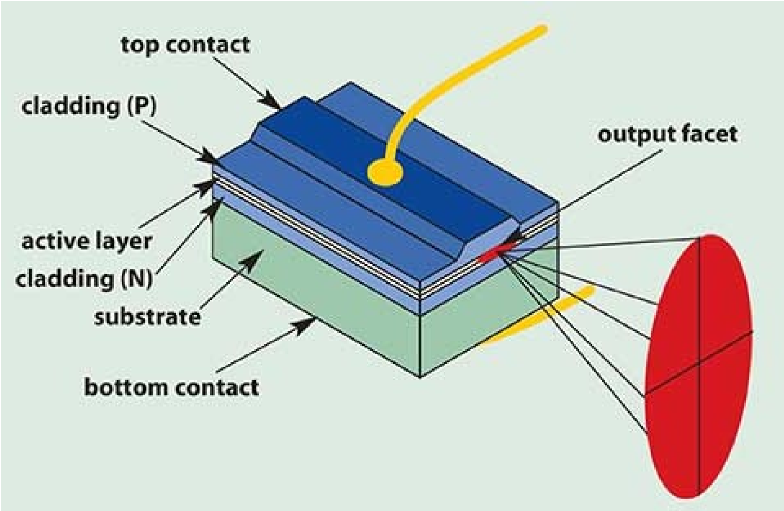
- The DH forms transverse confinement for both carriers and photons.
- The cleaved facets act as the mirrors (R=30%).
- The in-plane waveguide and the perpendicular mirrors form the resonant cavity.

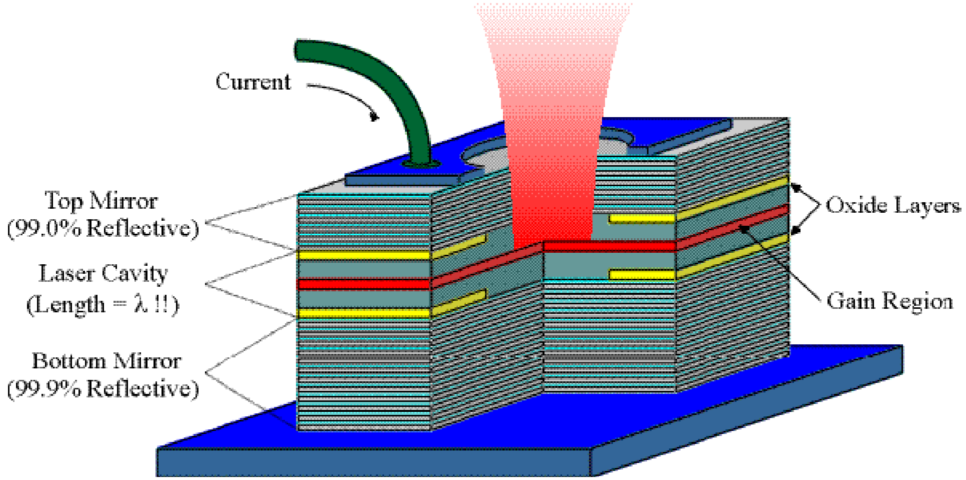


- In the separate confinement heterosturcture (SCH), a thin well (10 nm) confines the carriers, while a separate confinement region confines the photons.

上海科技大学 ShanghaiTech University

Edge-emitting laser and VCSEL



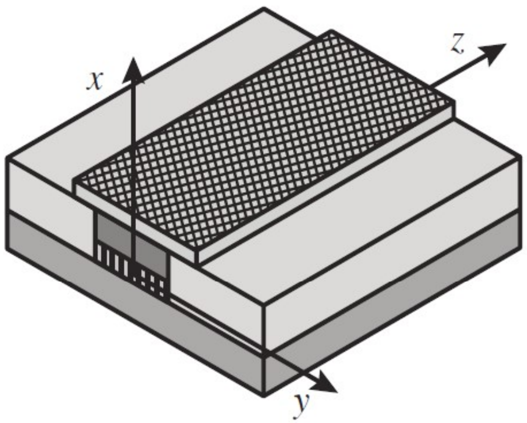


- Edge emitting laser: the light beam is parallel to the active region. The cavity mirror is formed by the cleaved facet.
- Vertical cavity surface emitting laser (VCSEL): the light beam is perpendicular to the active region. The mirror is formed by a multilayer reflective stack.

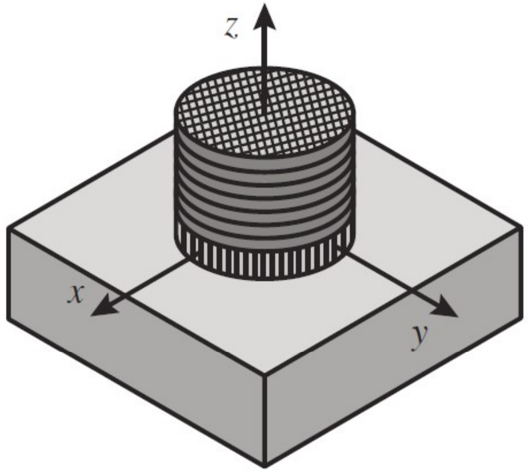
上海科技大学 ShanghaiTech University

Edge-emitting laser and VCSEL

- Practical laser must emit light in a narrow beam, so lateral patterning of the active region is necessary. The lateral (y) dimension is on the order of a few microns.



In-Plane



VCSEL

- The optical waveguide is sufficiently narrow to support only a single lateral mode, but sufficiently wide to support a relatively small diffraction angle, for coupling with optical fibers.
- For VCSELs, mutimode (lateral) is desirable for multimode fiber communications.

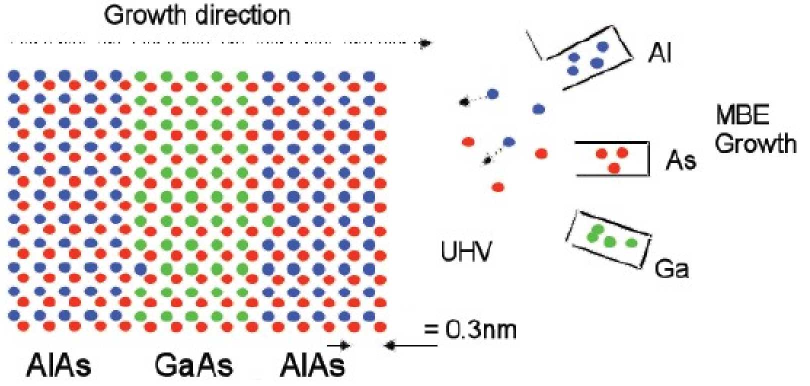
Epitaxial growth technology

Heterostructures are grown **epitaxially**, as lattice-matched layers of one semiconductor material over another, by

- molecular-beam epitaxy (MBE) uses **molecular beams** of the constituent elements in a high-vacuum environment,
- liquid-phase epitaxy (LPE) uses the **cooling of a saturated solution** containing the constituents in contact with the substrate (but layers are thick)
- vapor-phase epitaxy (VPE) and metal-organic chemical vapor deposition (MOCVD) use **gases in a reactor**.

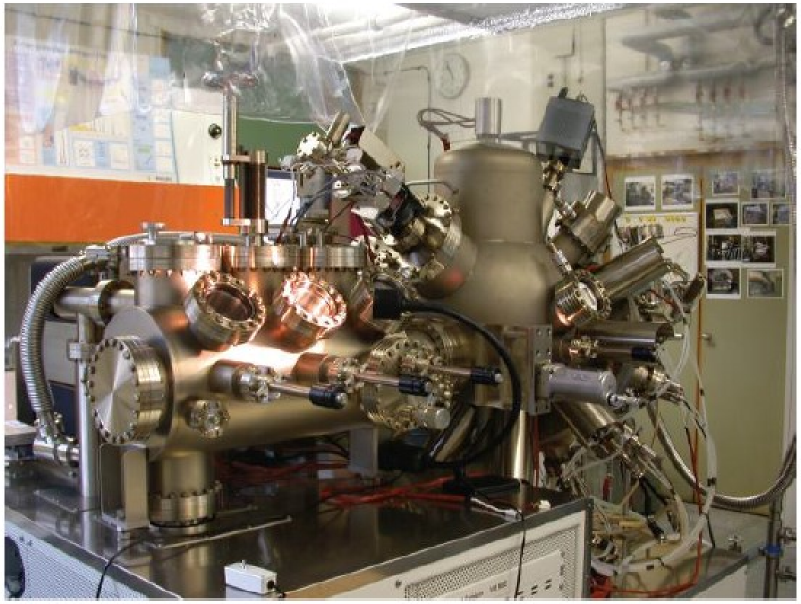
The performance of early laser diode was limited by manufacturing techniques

MBE



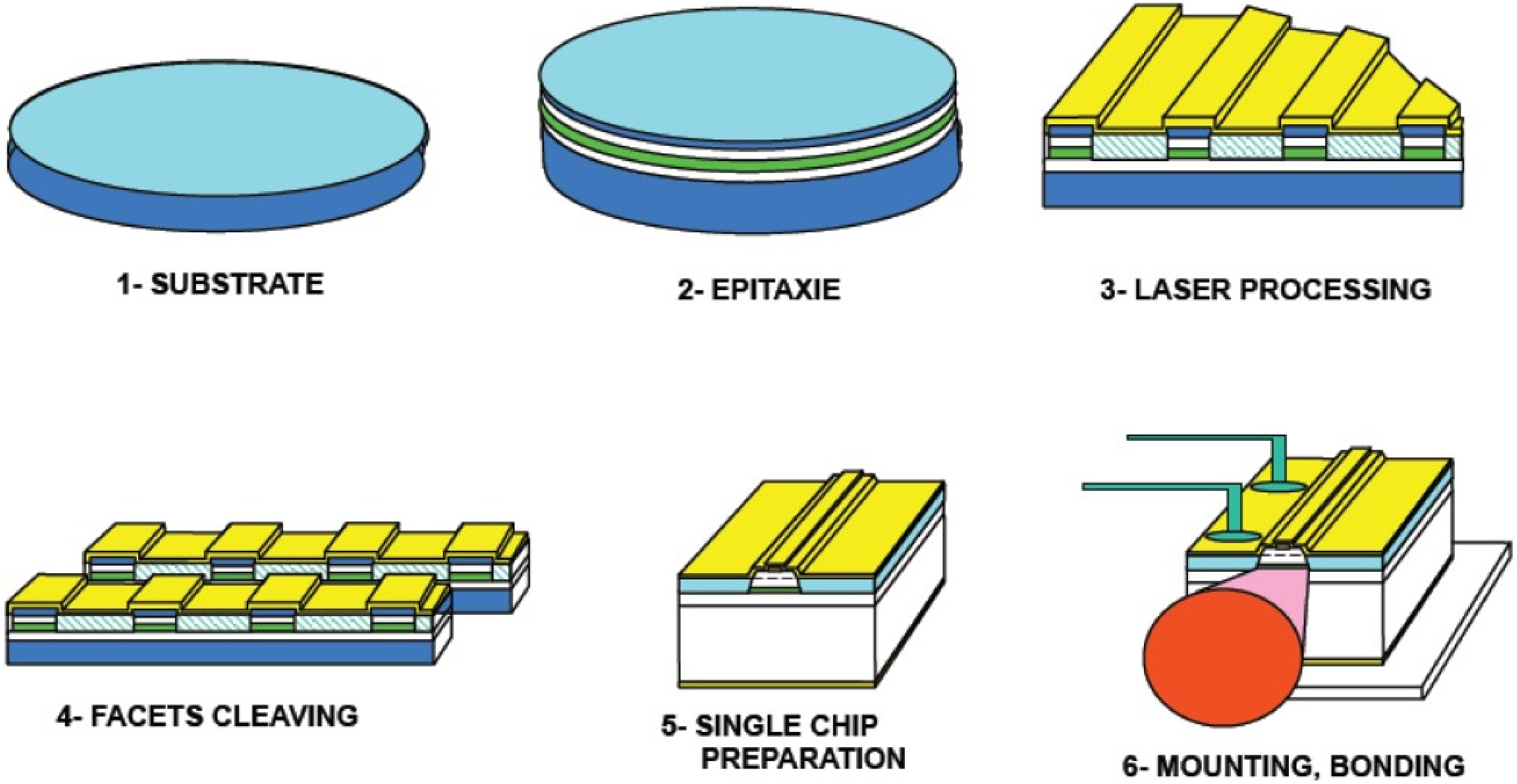
The compositions and dopings of the individual layers are determined by **manipulating the arrival rates** of the molecules and the **temperature** of the substrate surface.

MBE growth reactor



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

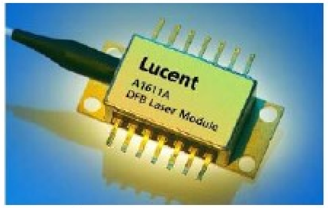
Fabrication techniques

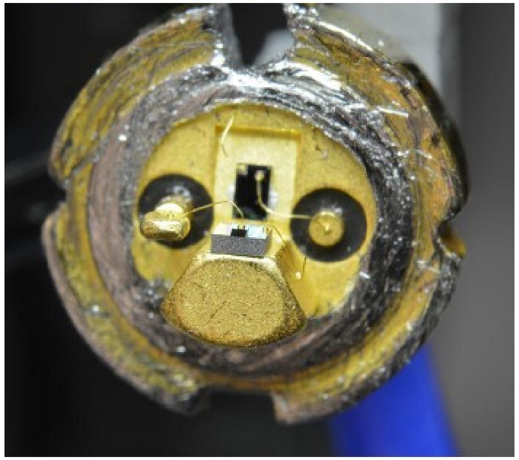


J. Fiast, ETHZ

Packaging

- Packaging allows **integrating laser diodes in devices**
  - Mechanical and optical coupling to an optical fiber
  - Temperature stabilization
  - Photodiode for monitoring of the optical power, with respect to pump current level.
  - Optical Isolation (avoid back reflections from the fiber)
- But: significantly **increases the fabrication cost**.





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

Laser diode: just the laser; **diode laser**: the complete system