ECE 340 Lectures 29
Solid State Electronic Devices

Spring 2022
10:00-10:50am

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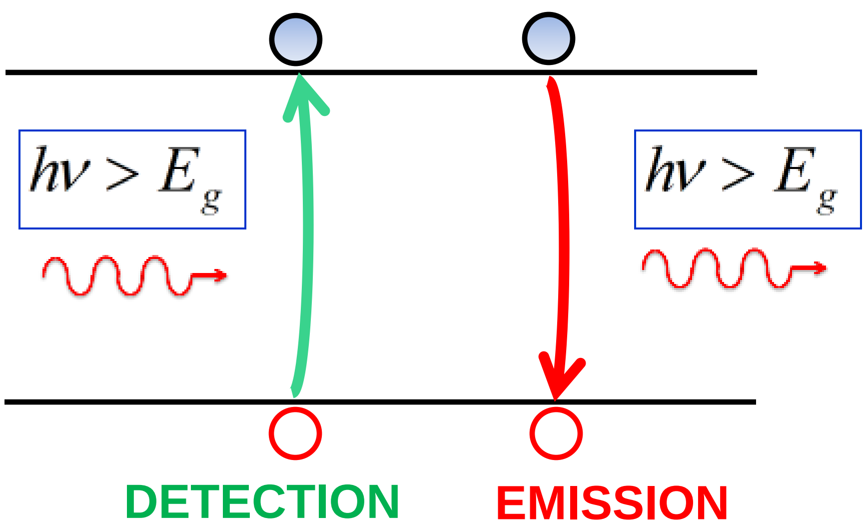
2062 ECE Building

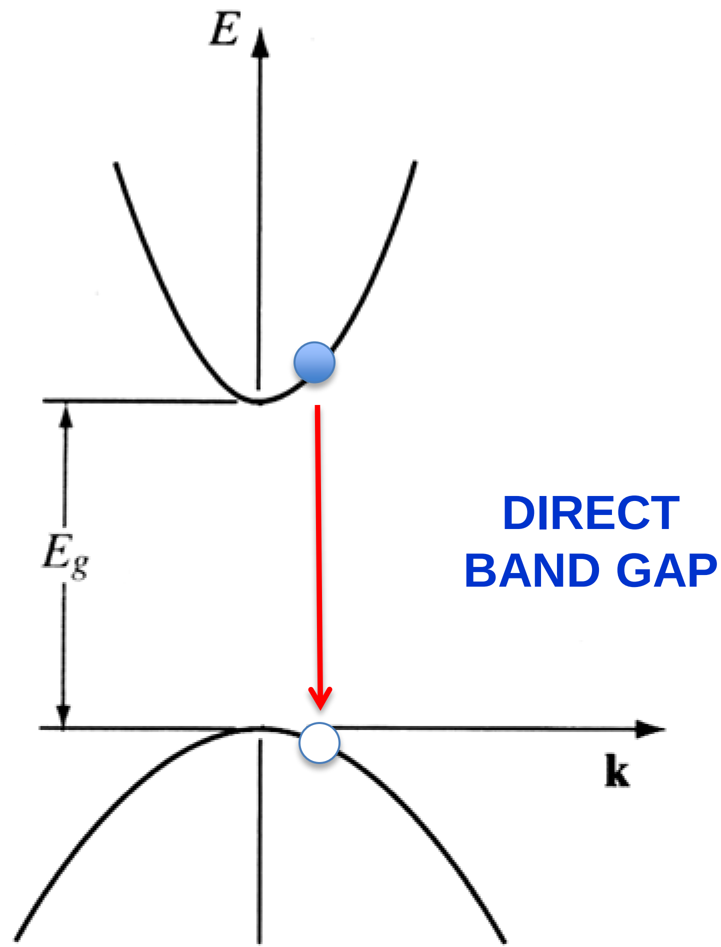
Today’s Discussion

- **LED (Light Emitting Diode)**
- **Semiconductor lasers**
- **Waveguiding in dielectric structures**

Light emission in semiconductor material

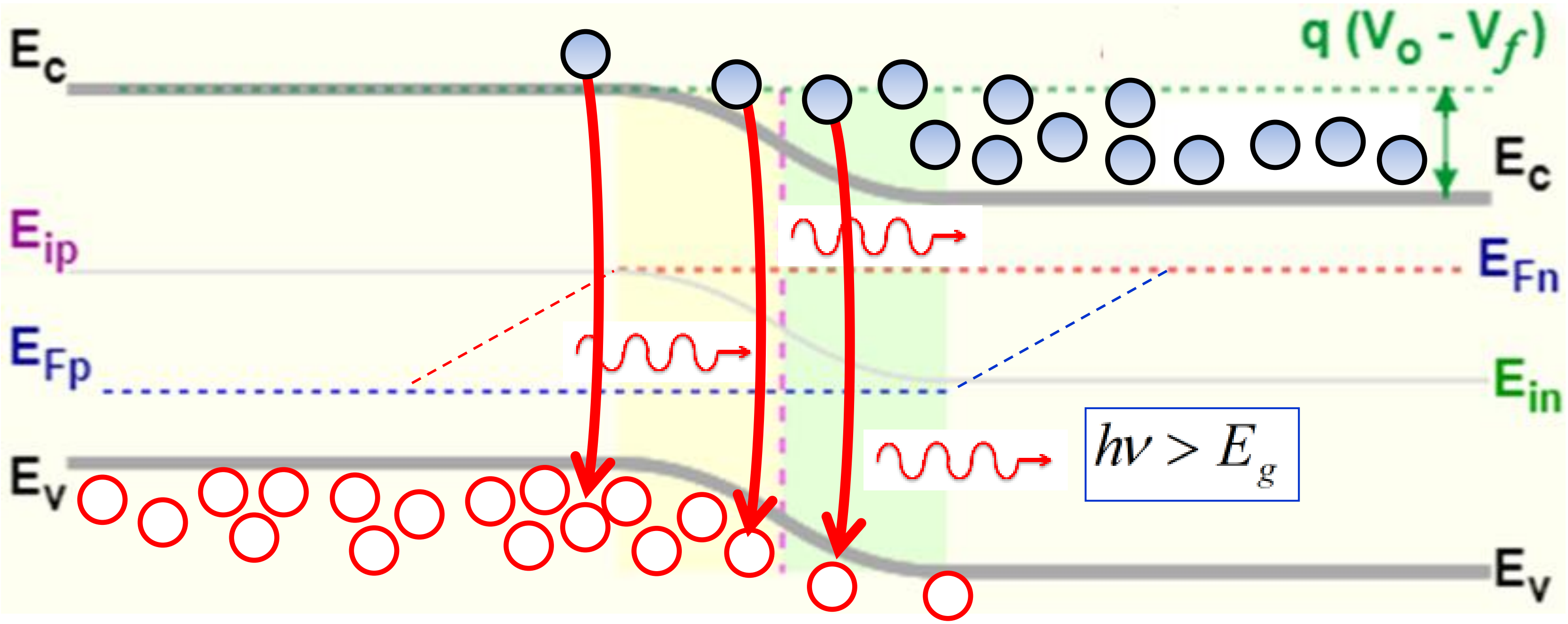
- **Light emission is the reverse process of light detection**





Light emission in *p-n* junction

- **Light emitting diode (LED) – We need to get a lot of electrons close to a lot of holes**



SPONTANEOUS (INCOHERENT) EMISSION IN TIME AND SPACE FOR EHP's IN PROXIMITY

Materials for different frequencies

λ [nm]	Color	Voltage	Materials
< 400 nm	Ultraviolet	3.1-4.4 V	AlN, AlGaN, AlGaInN
400-450 nm	Violet	2.8-4.0 V	InGaN
450-500 nm	Blue	2.5-3.7 V	InGaN, SiC
500-570 nm	Green	1.9-4.0 V	GaP, AlGaInP, AlGaP
570-590	Yellow	2.1-2.2 V	GaAsP, AlGaInP, GaP
590-610	Orange/Amber	2.0-2.1 V	GaAsP, AlGaInP
610-760	Red	1.6-2.0 V	AlGaAs, GaAsP, AlGaInP, GaP
> 760	Infrared	< 1.9 V	GaAs, AlGaAs, InGaAsP

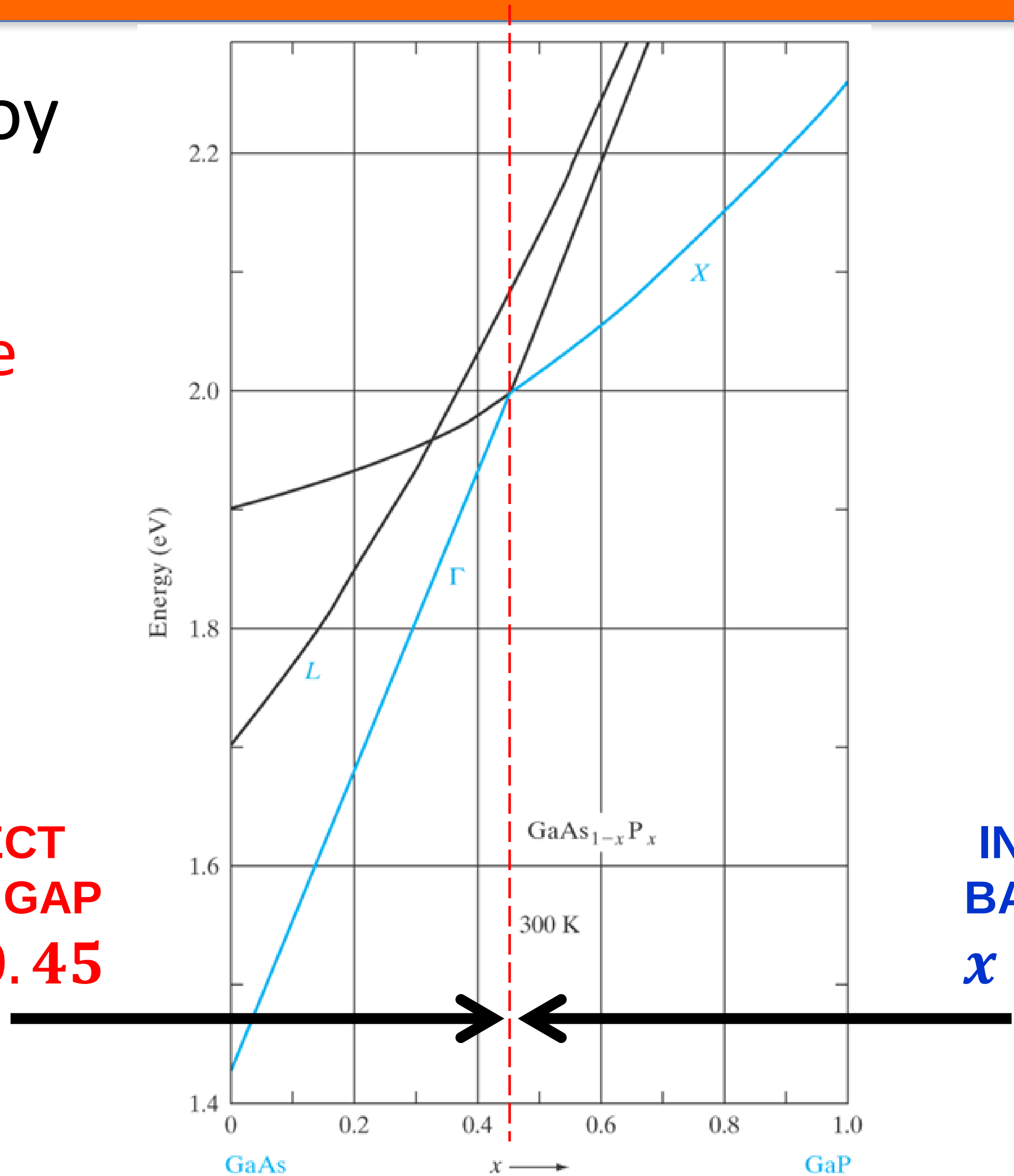
A very important LED material: $GaAs_{1-x} P_x$

- $GaAs_{1-x} P_x$ alloy

Valley minima in momentum space

Γ = direct

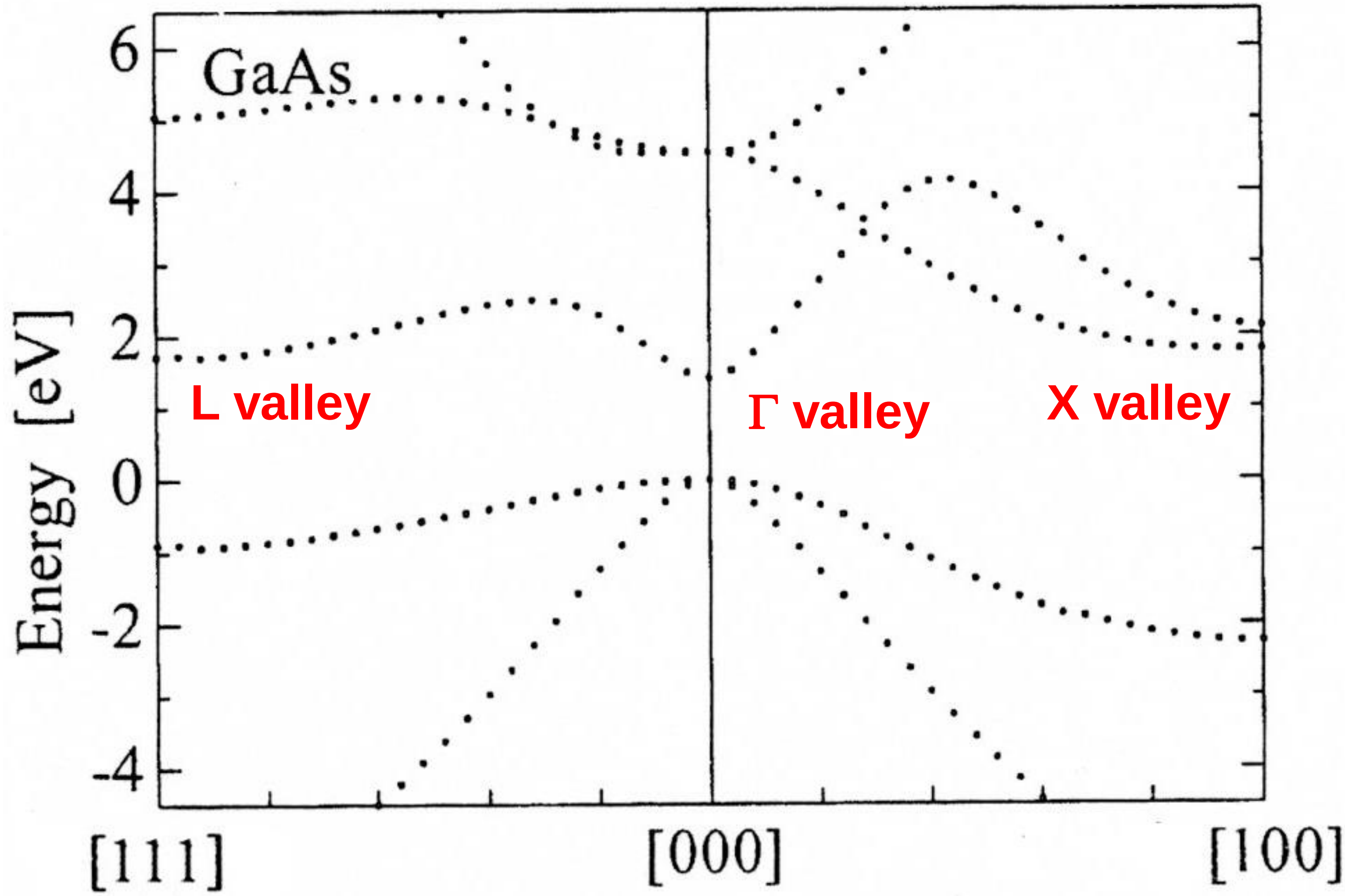
L & X = indirect



DIRECT BAND GAP $x < 0.45$

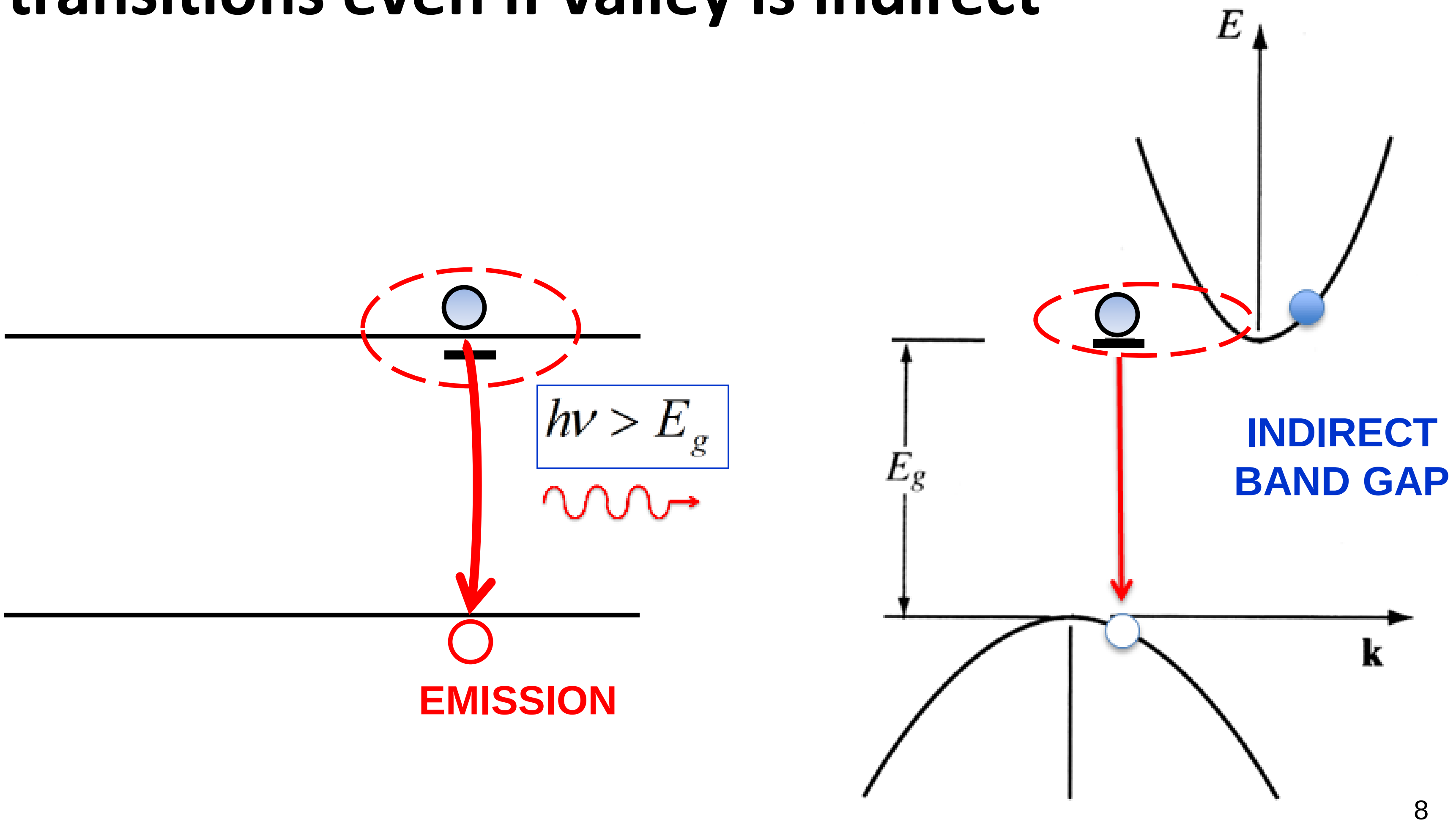
INDIRECT BAND GAP $x > 0.45$

GaAs reference band structure

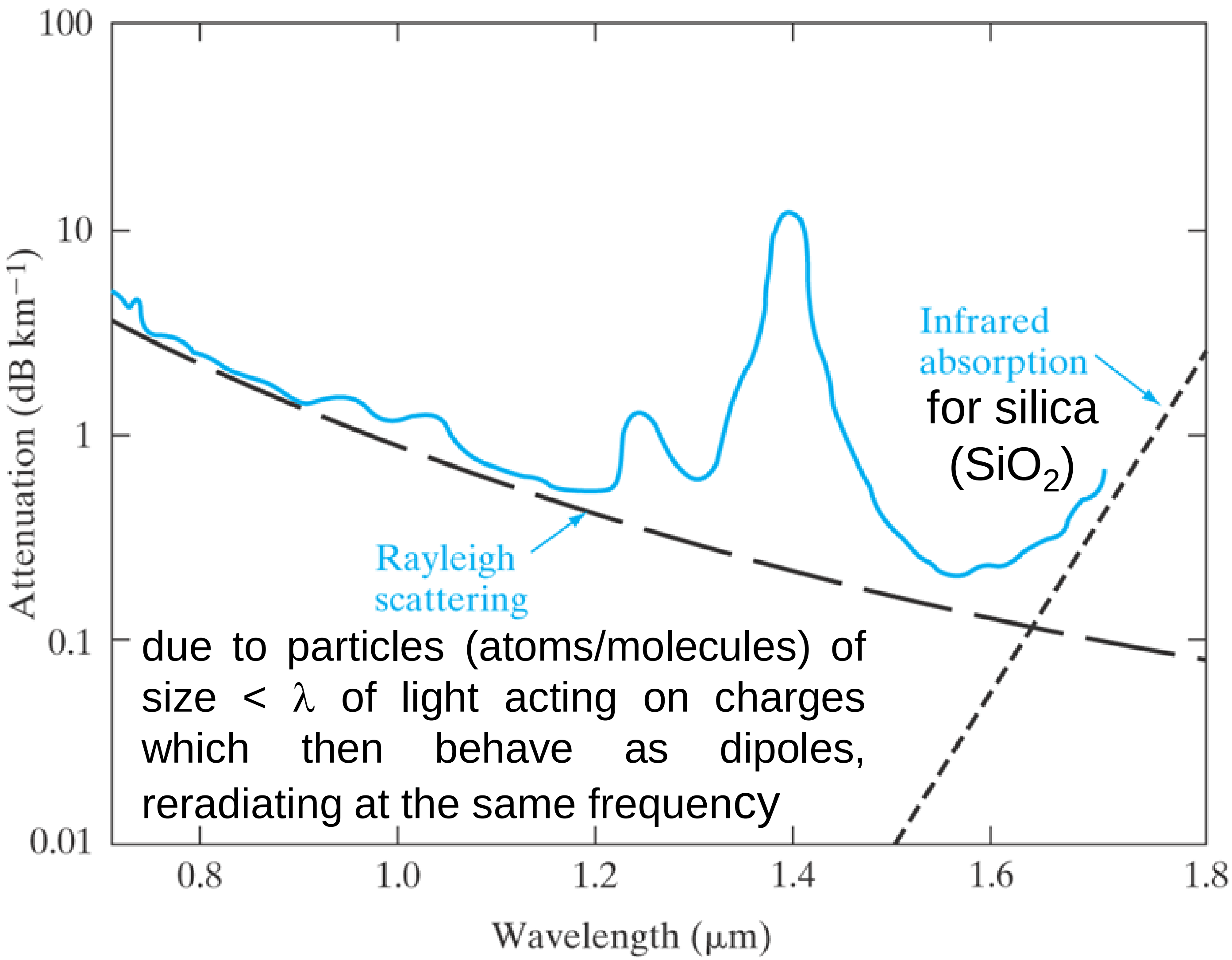


Emission in indirect material: $GaAs_{1-x} P_x$

- **Certain impurities (Nitrogen) allow direct transitions even if valley is indirect**



Fiber optics: Why infrared light?



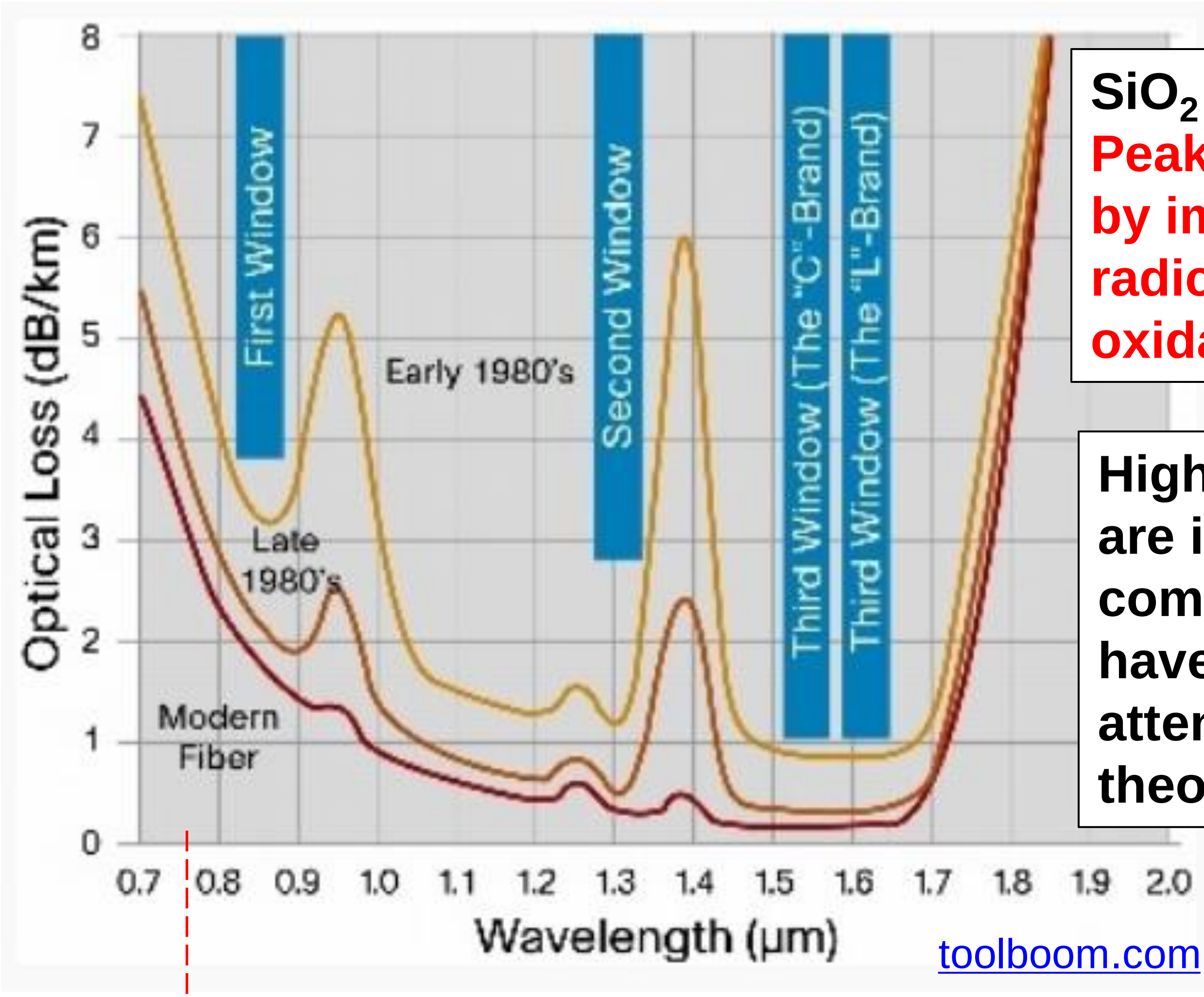
for silica (SiO_2)

due to particles (atoms/molecules) of size < λ of light acting on charges which then behave as dipoles, reradiating at the same frequency

From *Solid State Electronic Devices,* Sixth Edition, by Ben G. Streetman and Sanjay Kumar Banerjee.

Fiber optics communications

- **Commercial links started in 1984**



toolboom.com

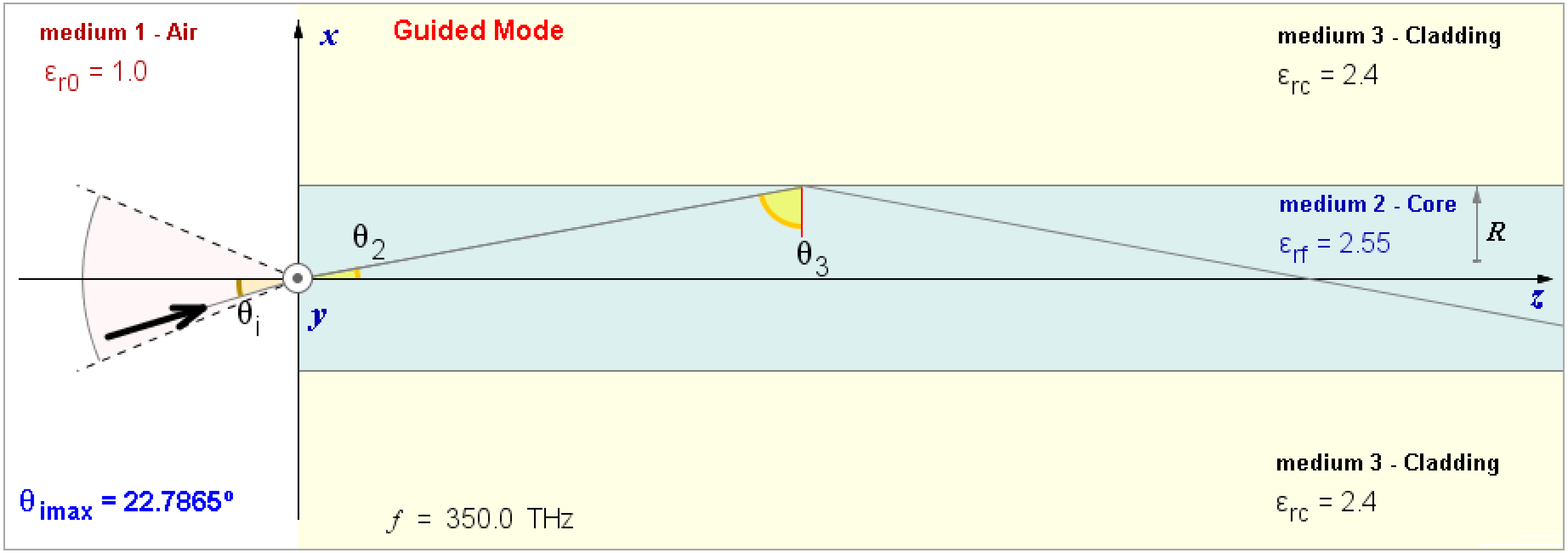
SiO_2 (glass) fibers
Peaks are due to absorption by impurities, mainly OH^- radicals, released during oxidation process.

Highly purified modern fibers are ideal for long-distance communication links, and have reached $\alpha < 0.15$dB/km attenuation, close to the theoretical limit

infrared range

How do optical fibers guide light?

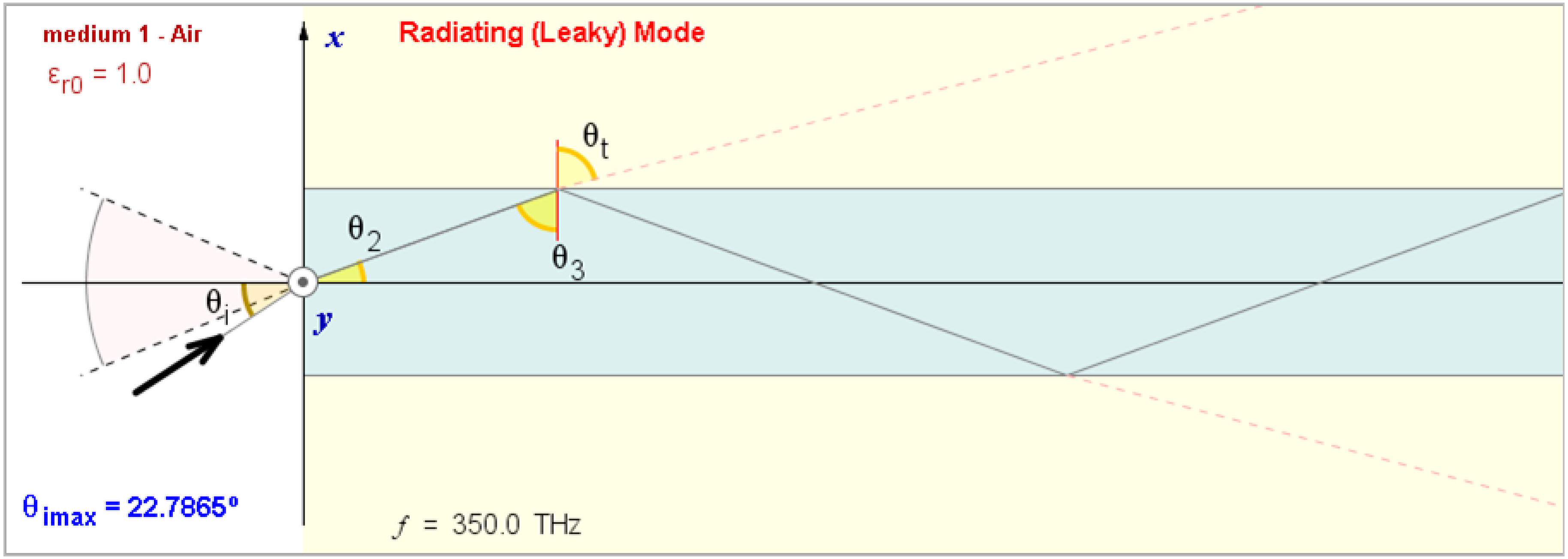
- **Total internal reflection at the interface between core and cladding**



permittivity ε (or index of refraction $n = \sqrt{\varepsilon}$) in the core must be higher than in the cladding for total reflection

How do optical fibers guide light?

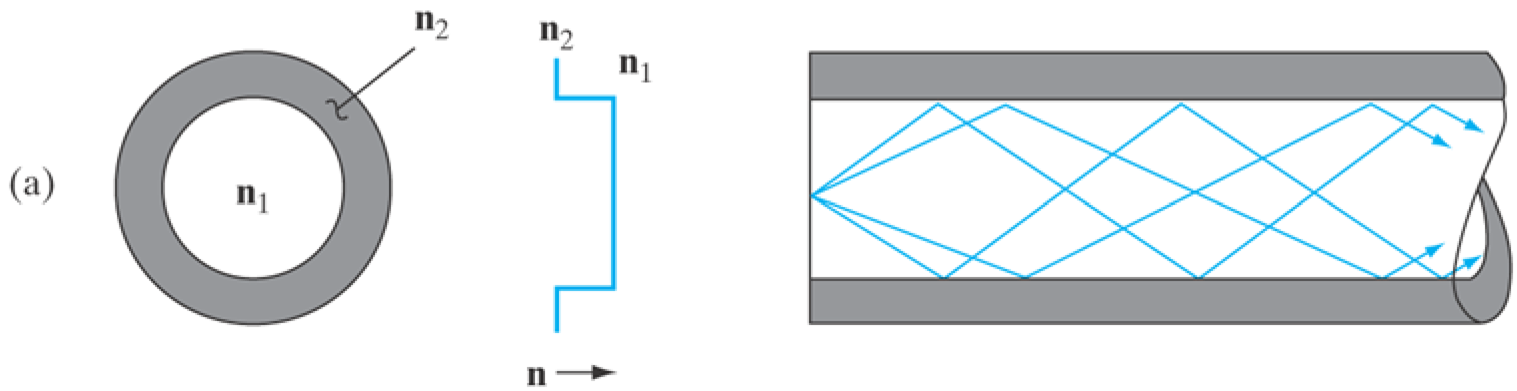
- **Entrance beyond the maximum angle causes radiation into the cladding (loss of power)**



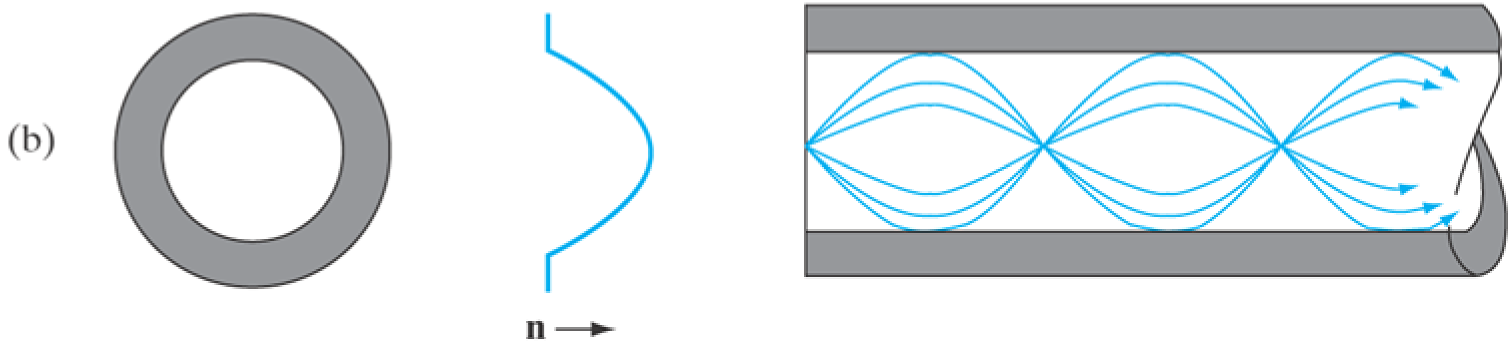
modes are leaky and dissipate quickly along length of fiber

Classification of fibers - 1

- **Step-index (uniform core)**



- **Graded index (core has maximum permittivity along the axis for self-focusing effect)**



Classification of fibers - 3

- **Multimode fiber –** It has fairly large core diameter (typically 200 μm for step-index – 50μm or 62.5μm for graded-index) and allows propagation of a range of angles.
- Suitable for short distances, up to 2km. Bandwidth of standard 300m to 400m Ethernet links is 10 Gigabits (graded index). It normally operates at 850nm or 1.3 μm with LED or VCSEL.

Classification of fibers - 4

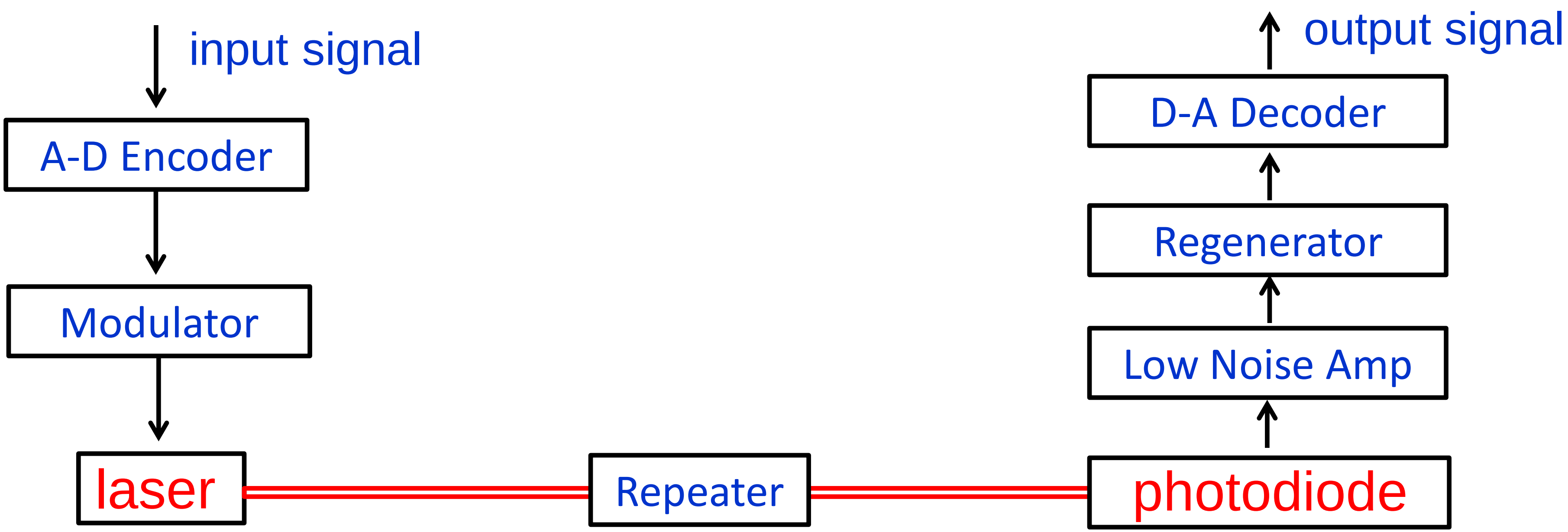
- **Monomode fiber –** It has narrow core diameter (8 μm or 10.5 μm) and it allows only axial propagation. In single mode there is no appreciable dispersion so bandwidth (or length of communication link) can be much greater.
- It uses higher performance quantum well lasers (1.3 μm or 1.55 μm) and very sensitive detectors over long-haul links.

Fiber optic links

- **Signal intensity in a fiber behaves as**

$$P(x) = P_0 \exp(-\alpha x)$$

where α is the power attenuation coefficient.



Semiconductor Laser

LASER =

Light

Amplification by

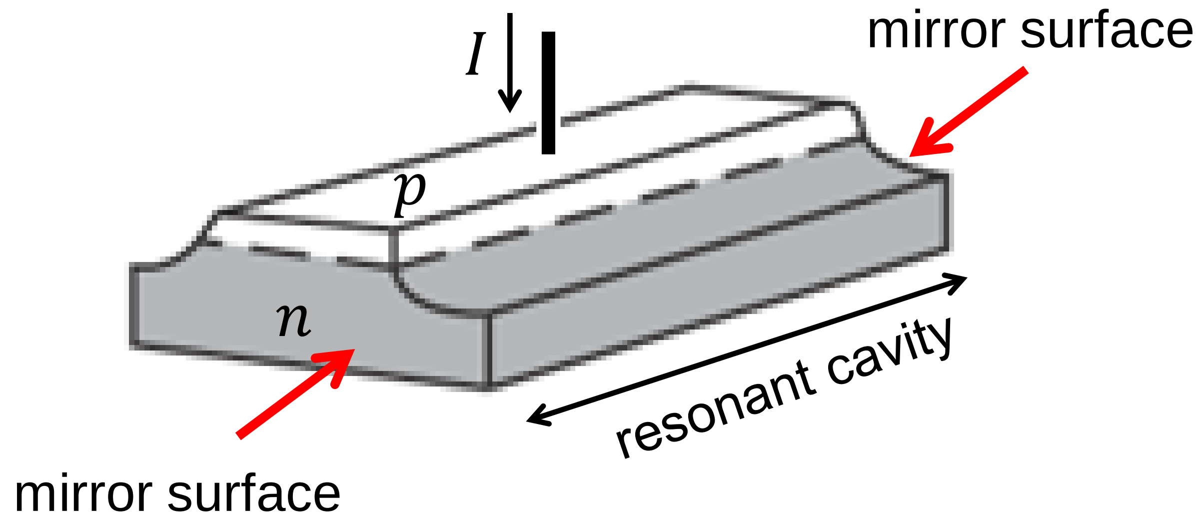
Stimulated

Emission of

Radiation

Semiconductor Laser

- **Simple *p-n* junction (e.g., GaAs)**

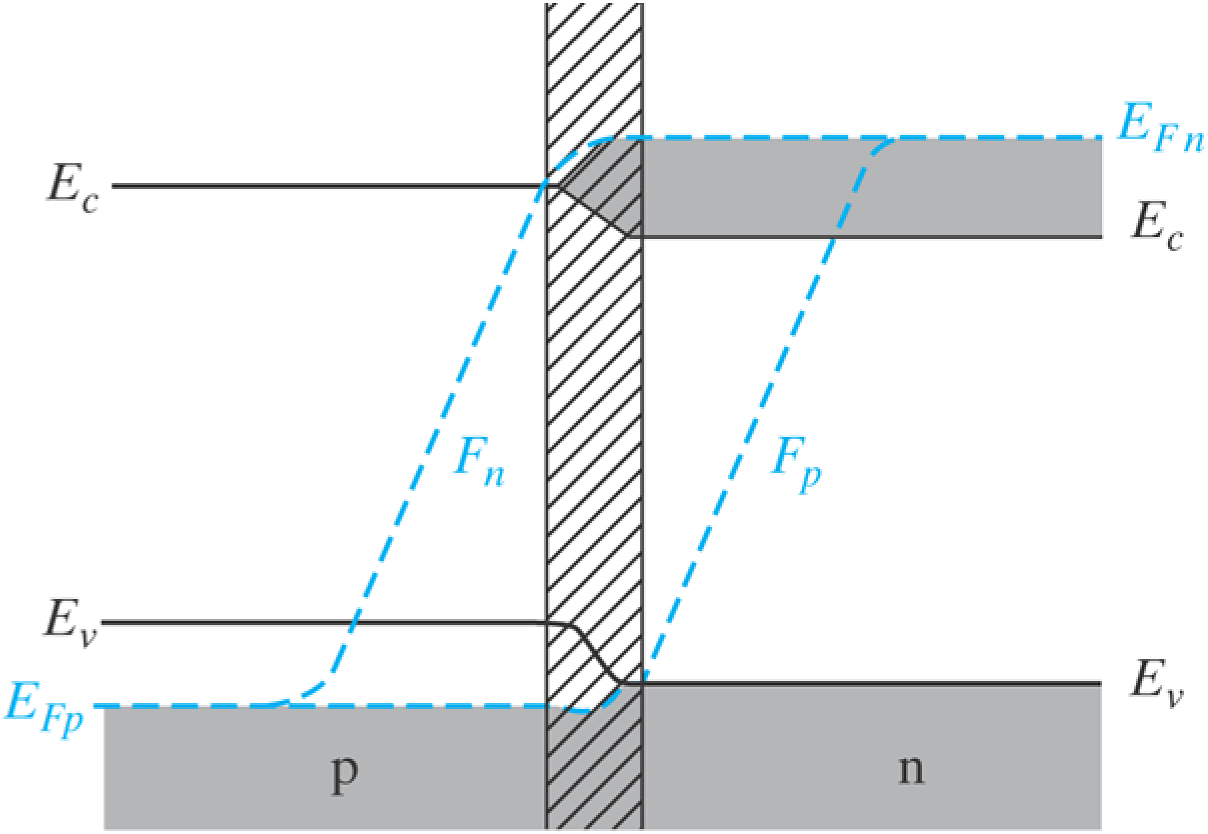


Two ingredients are needed to make a laser:

- population inversion (stable population of excited states)
- resonant cavity to build up a coherent photon population for stimulated emission to occur (coherence)

Population Inversion

- **Heavily doped *p-n* junction in forward bias**



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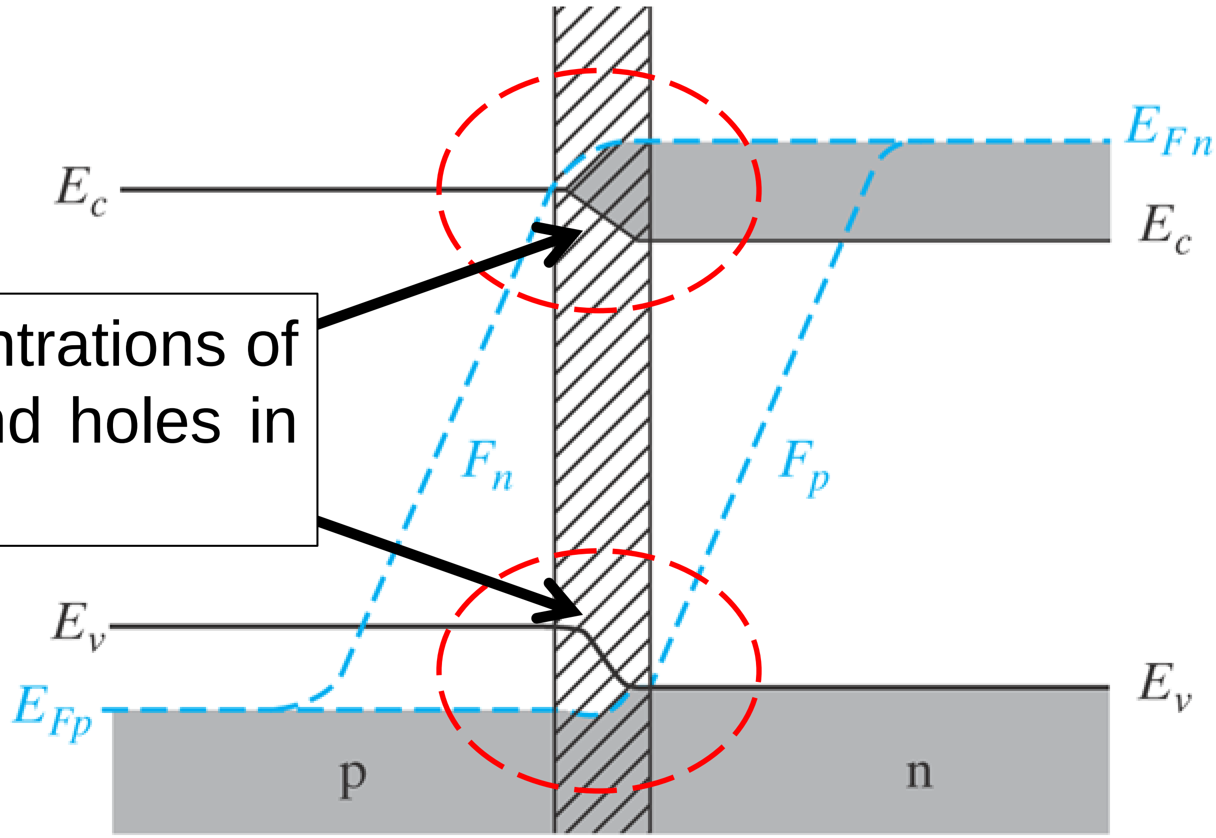
Population Inversion

- **Heavily doped *p-n* junction in forward bias**

large concentrations of electrons and holes in proximity



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Population Inversion

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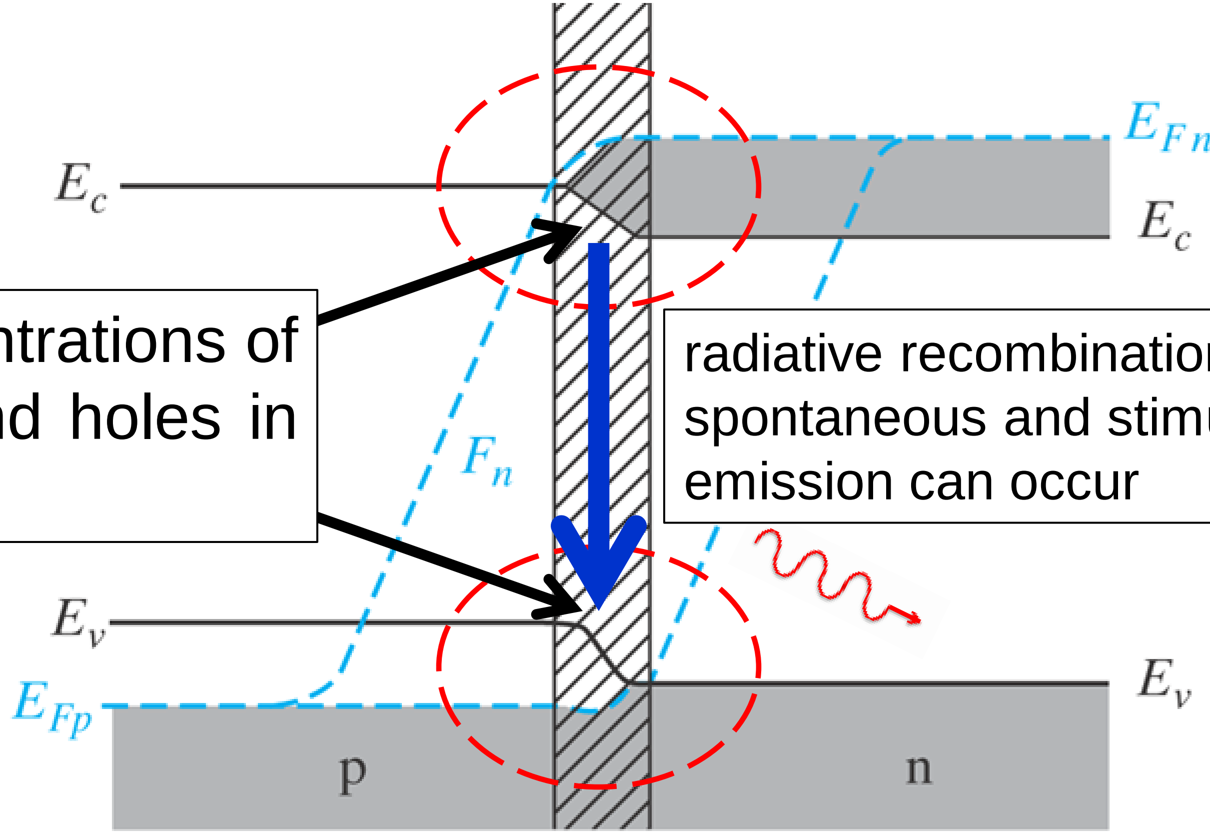

large concentrations of electrons and holes in proximity

radiative recombination: spontaneous and stimulated emission can occur

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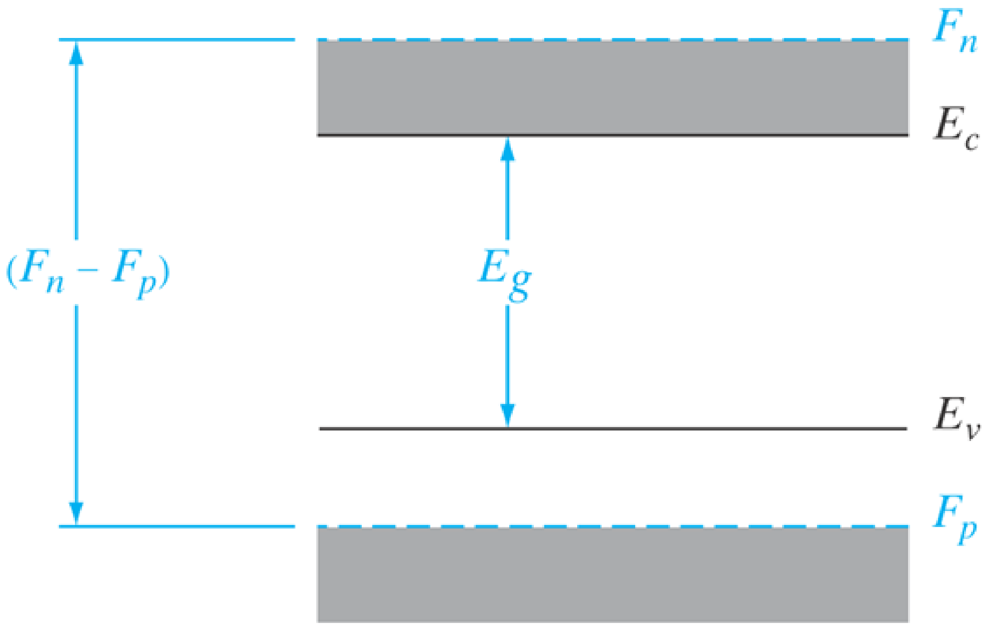
Population inversion

$$n = N_C \exp\left(\frac{E_C - F_n}{k_B T}\right) = n_i \exp\left(\frac{F_n - E_i}{k_B T}\right)$$

$$p = N_v \exp\left(\frac{F_p - E_V}{k_B T}\right) = n_i \exp\left(\frac{E_i - F_p}{k_B T}\right)$$



electrons can recombine approximately in the range of energies

$$E_g < h\nu < (F_n - F_p)$$

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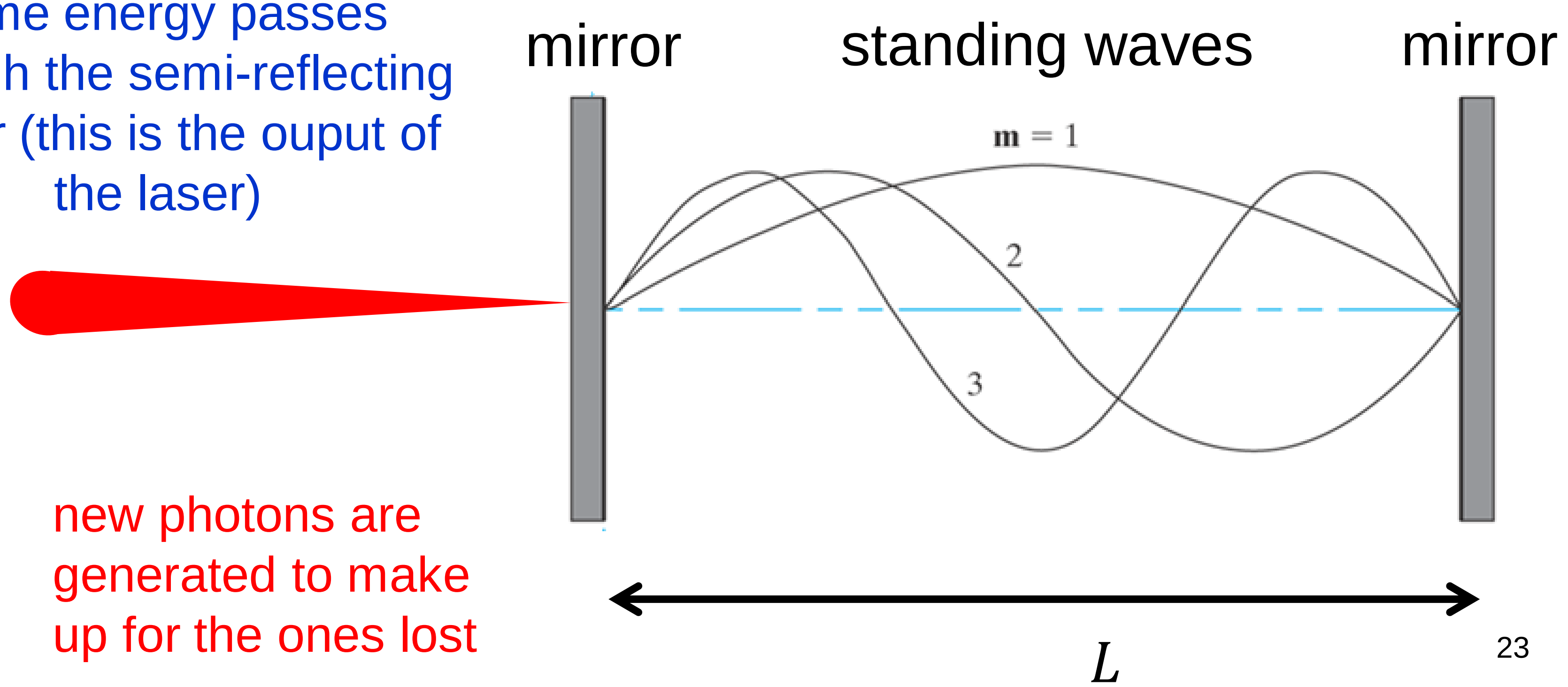
Cavity modes

$$L = \boldsymbol{m}\frac{\lambda}{2} \qquad \boldsymbol{n} = \sqrt{\varepsilon} \qquad \lambda_0(vacuum) = \lambda\boldsymbol{n}$$

$$\boldsymbol{m} = \frac{2L}{\lambda_0}\boldsymbol{n}$$

some energy passes through the semi-reflecting mirror (this is the ouput of the laser)



new photons are generated to make up for the ones lost

Stimulated emission

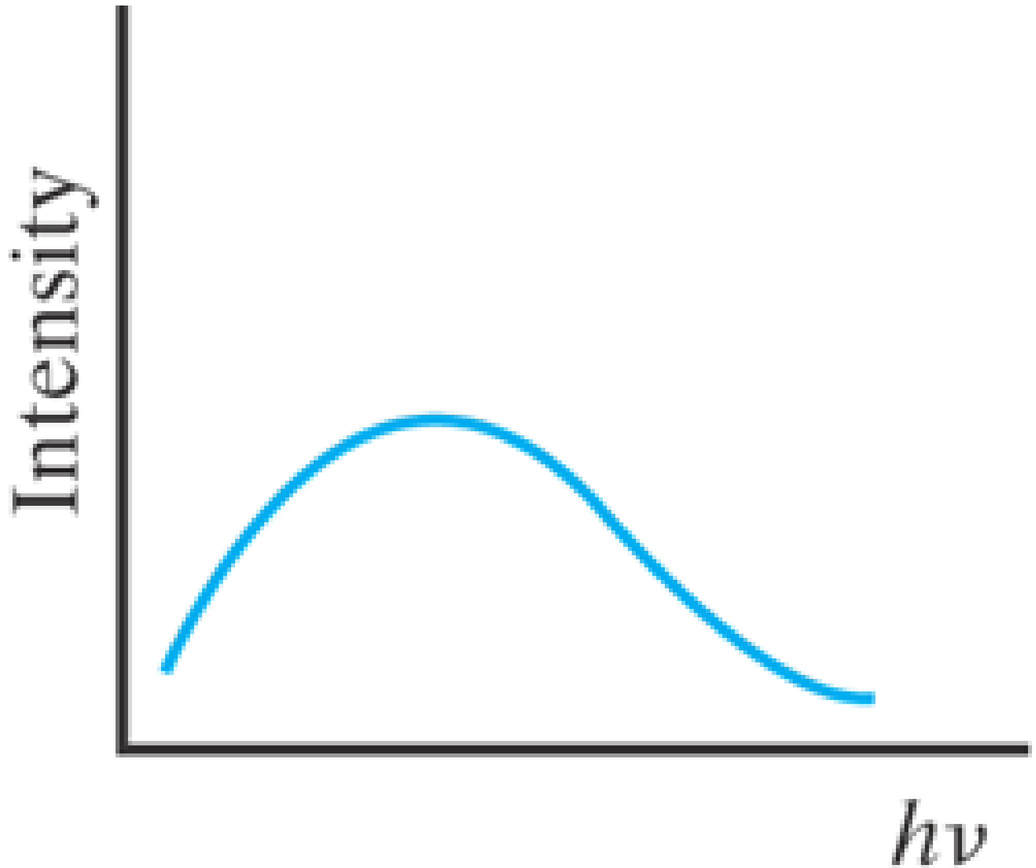
The process by which an incoming photon of specific frequency interacts with an excited electron, causing it to drop to a lower energy level (recombine) emitting a second phonon with the same:

- frequency
- phase
- direction
- polarization

This reinforces the coherent oscillation, replenishing photons lost through the mirror.

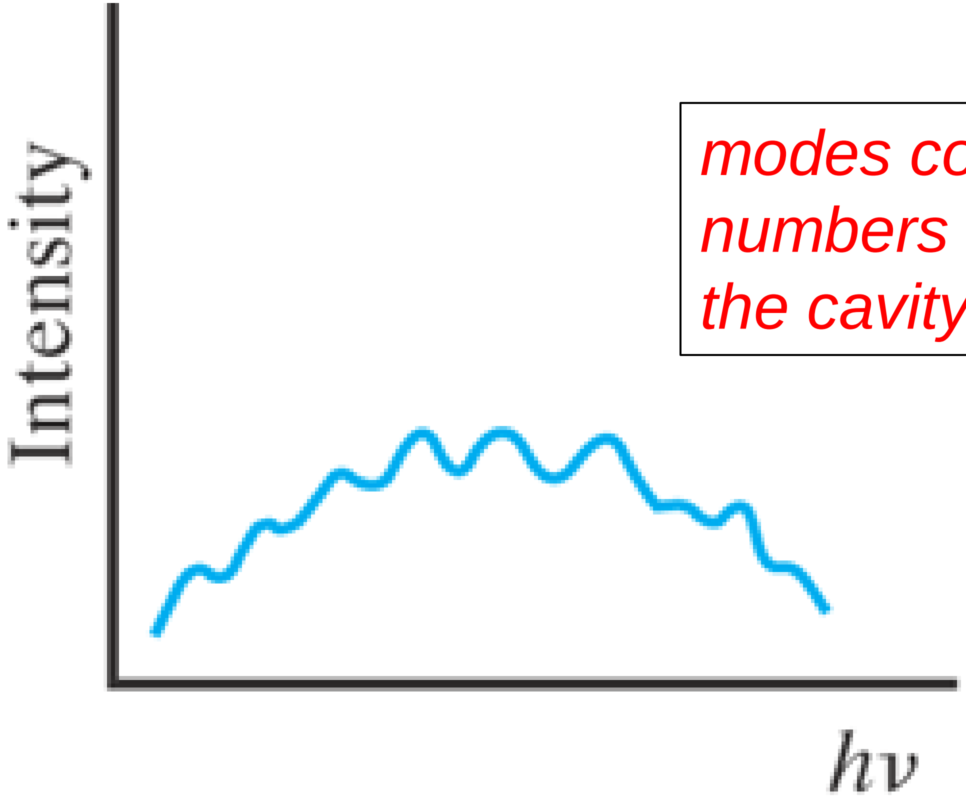
Below threshold

At *low current levels*, **spontaneous emission** dominates (incoherent emission) in the whole range of possible frequencies (behaving like LED):



Approaching threshold

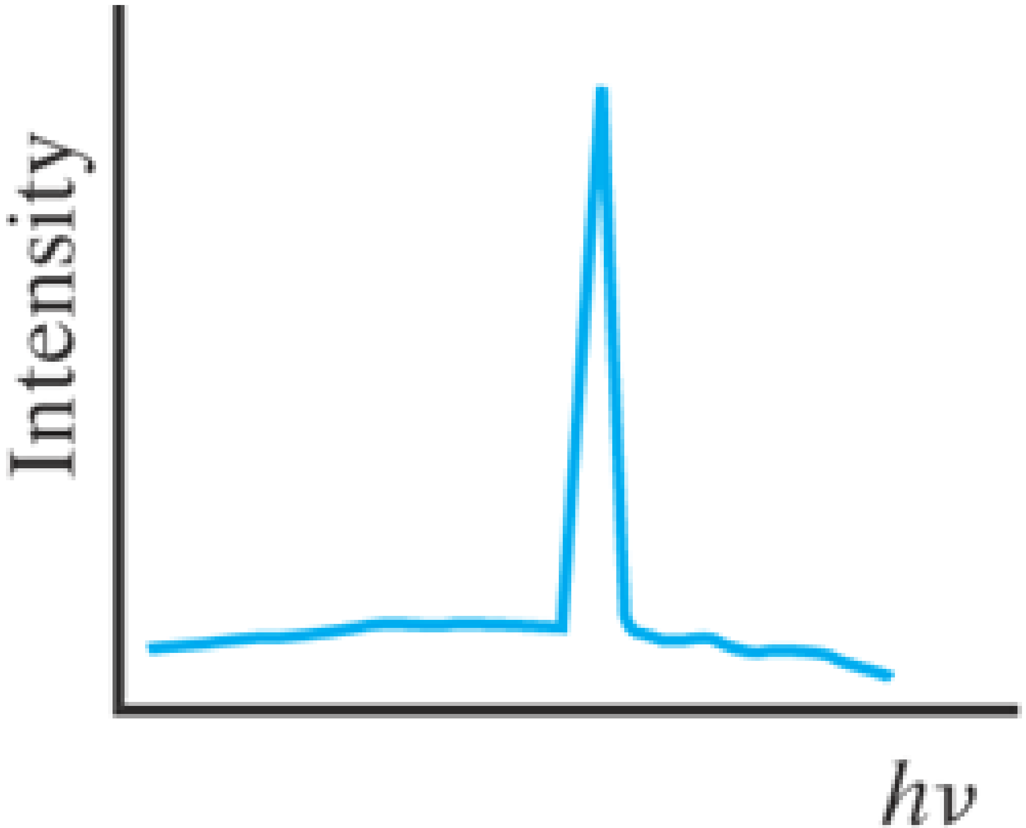
The photon wavelengths participating in the **stimulated emission** are determined by the length of the laser resonant cavity. As current increases, various cavity modes start to appear



modes correspond to successive numbers of integer $\lambda/2$ that fit in the cavity

The cavity structure favors stimulated emission

At *high current levels (above threshold)*, **stimulated emission** dominates (coherent emission) favoring a dominant mode:



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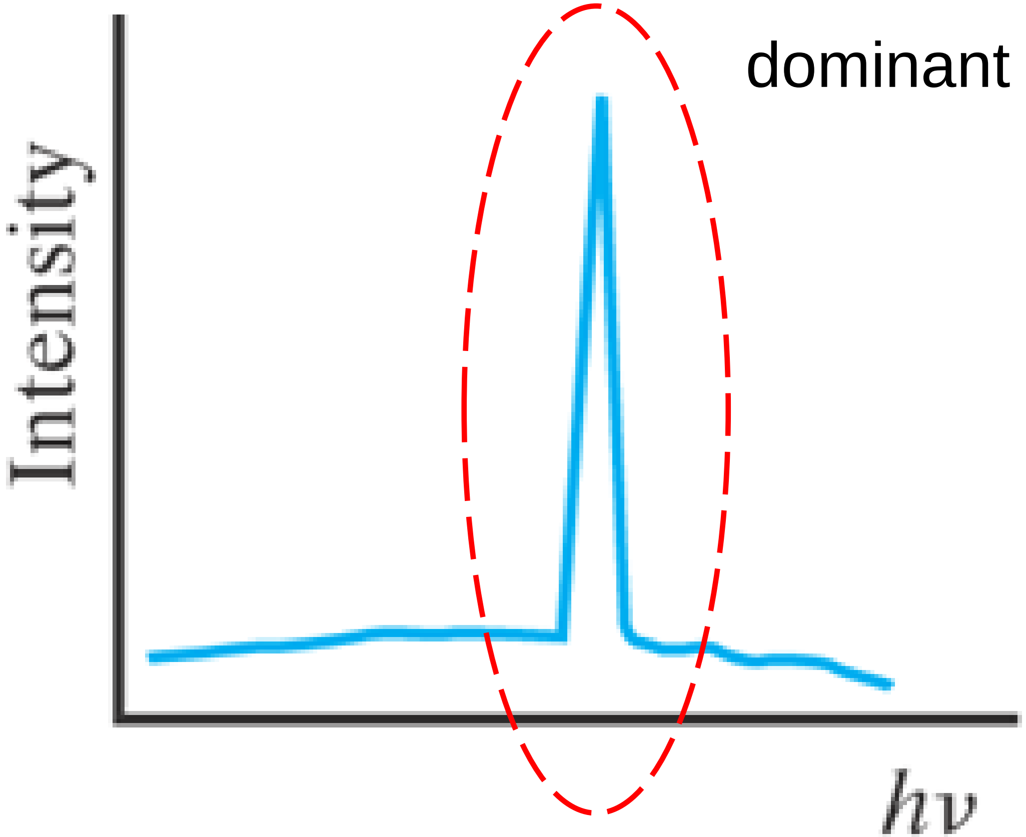

dominant nearly monochromatic radiation

The cavity structure favors stimulated emission

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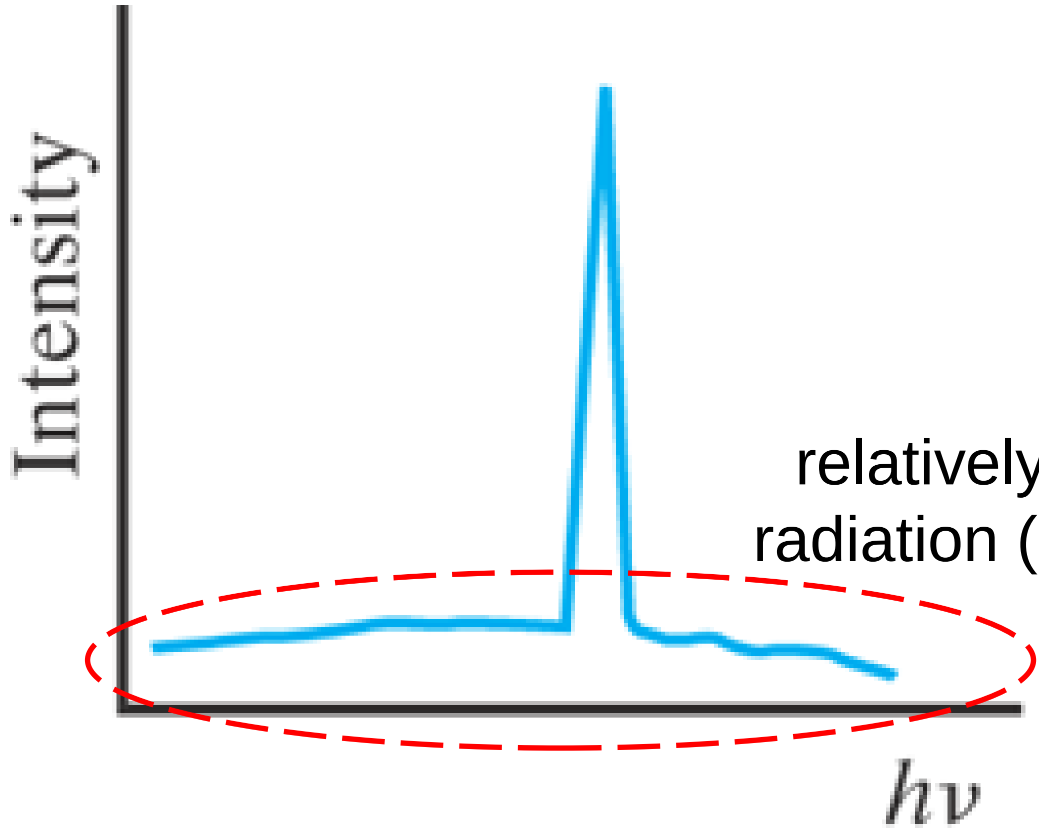
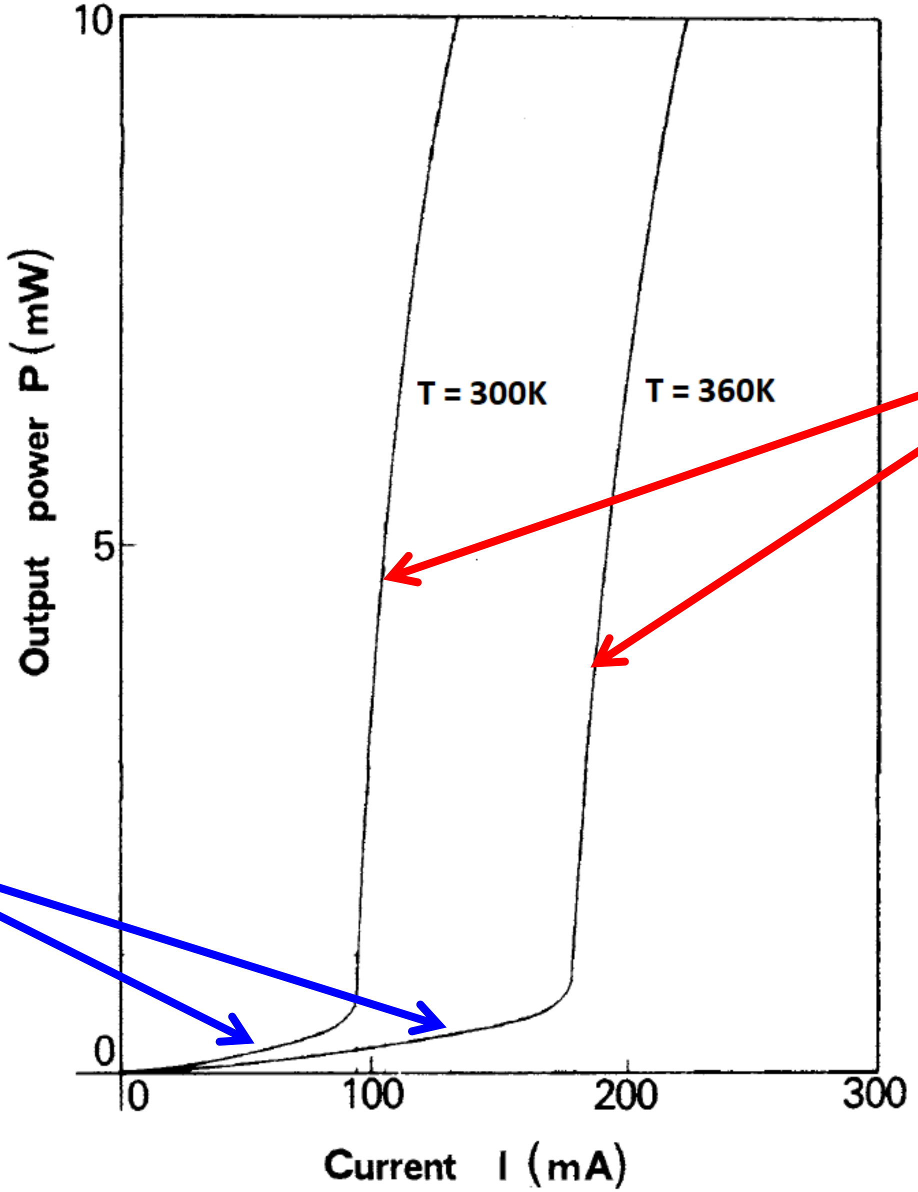


relatively weak background radiation (mainly spontaneous emission)

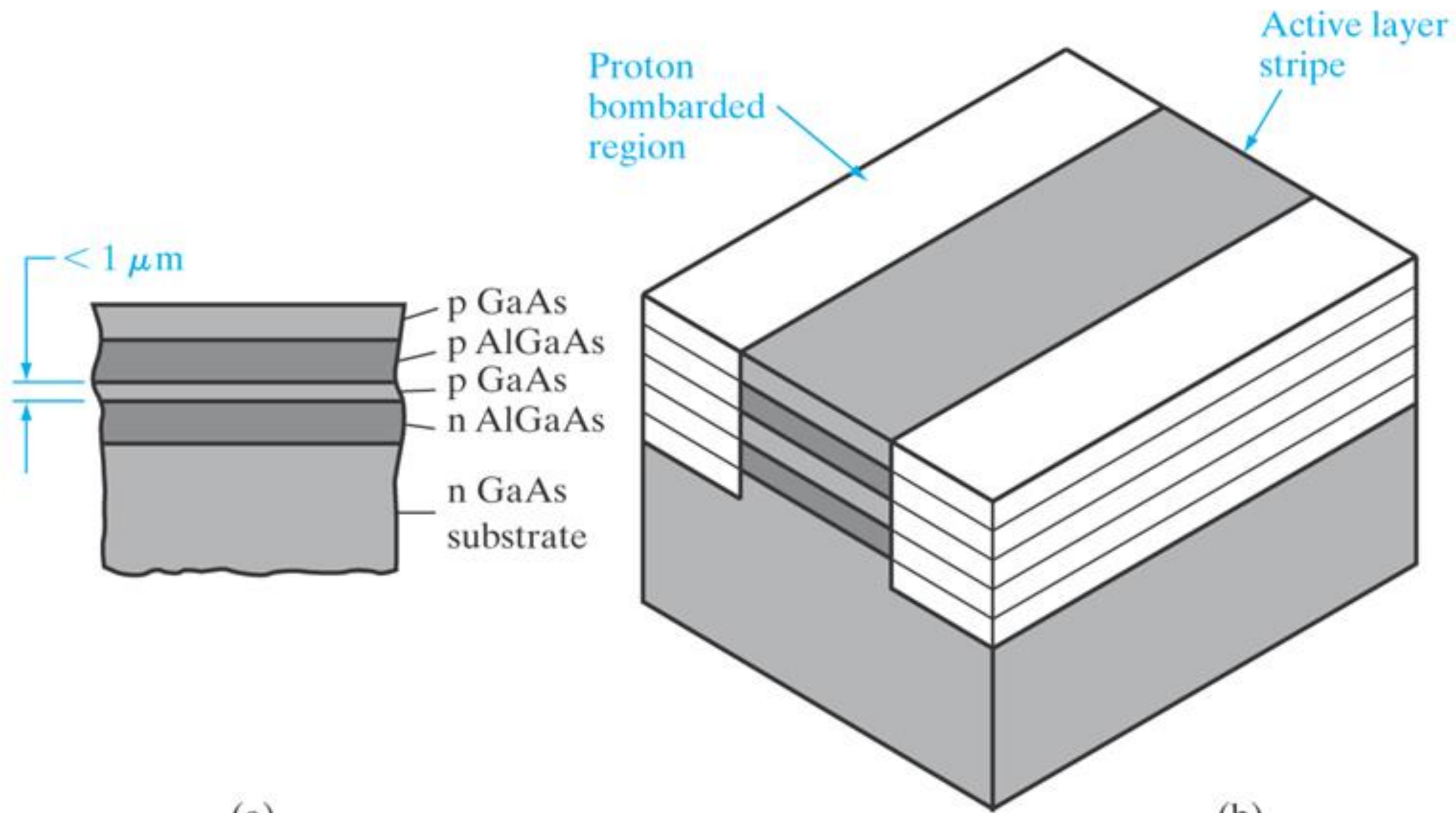
Laser – Power emission characteristics



Above threshold stimulated emission dominates

Below threshold spontaneous emission dominates

Modern Double Heterojunction Laser



(a) (b)

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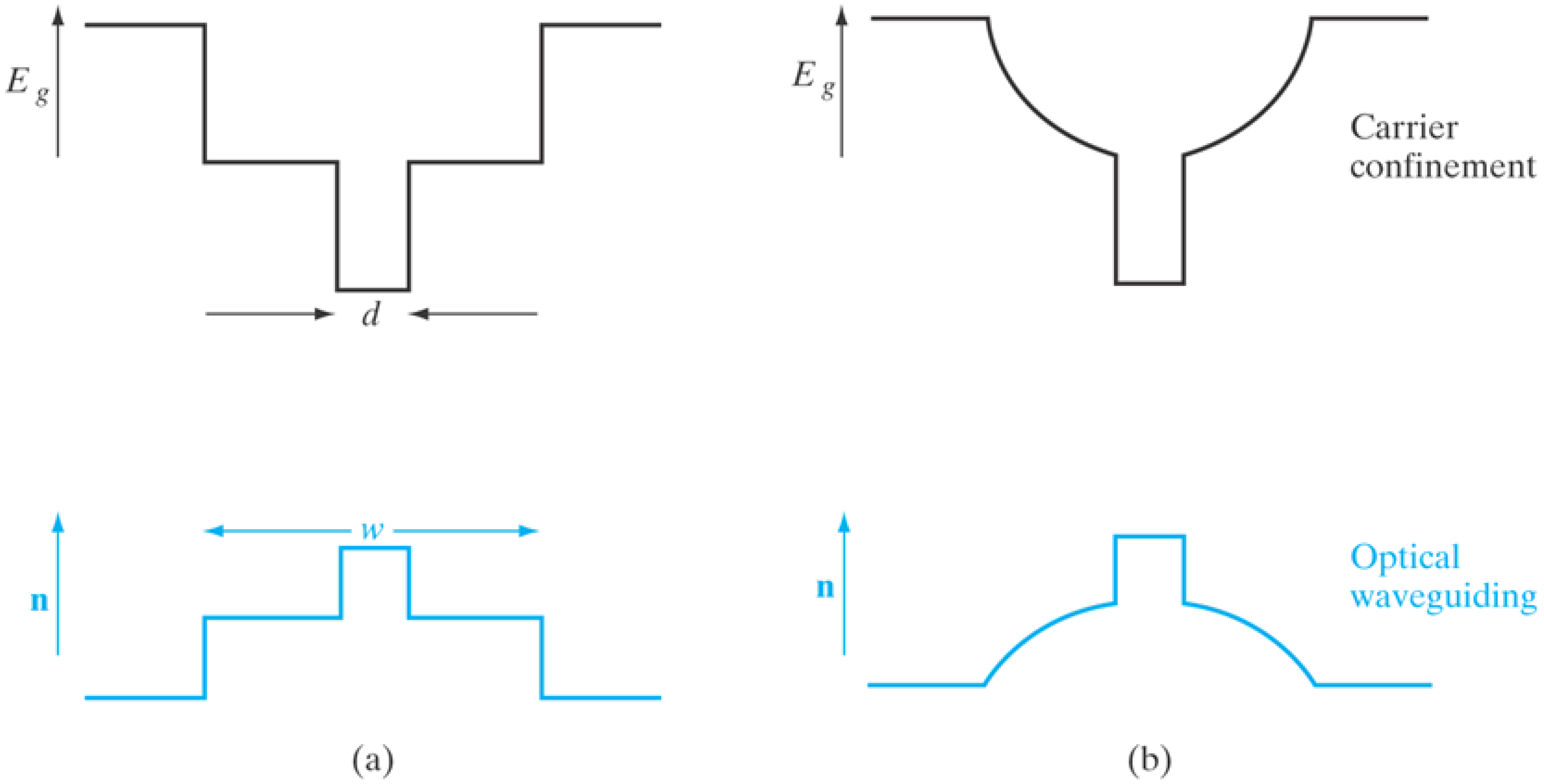
Optical waveguiding and Carrier confinement



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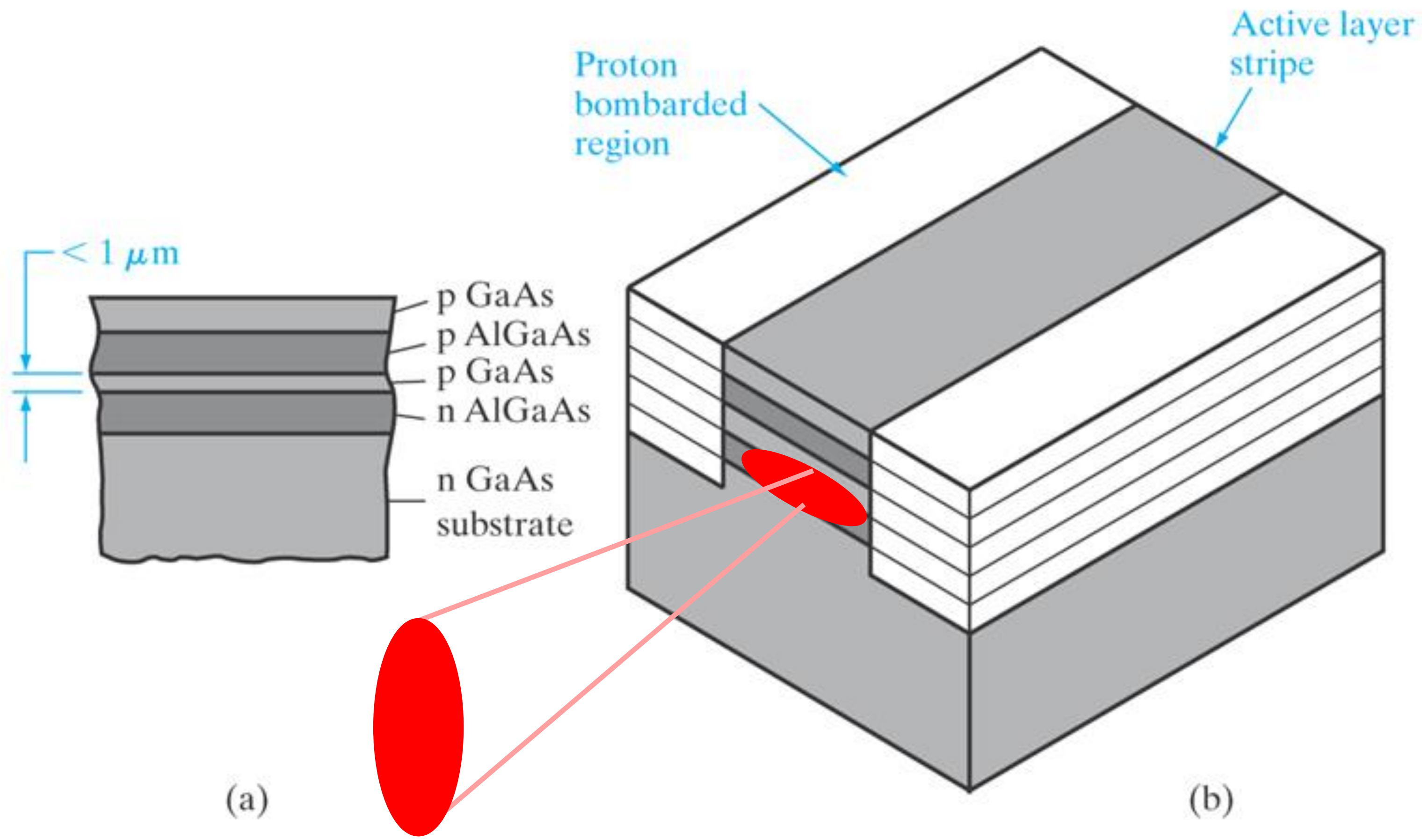
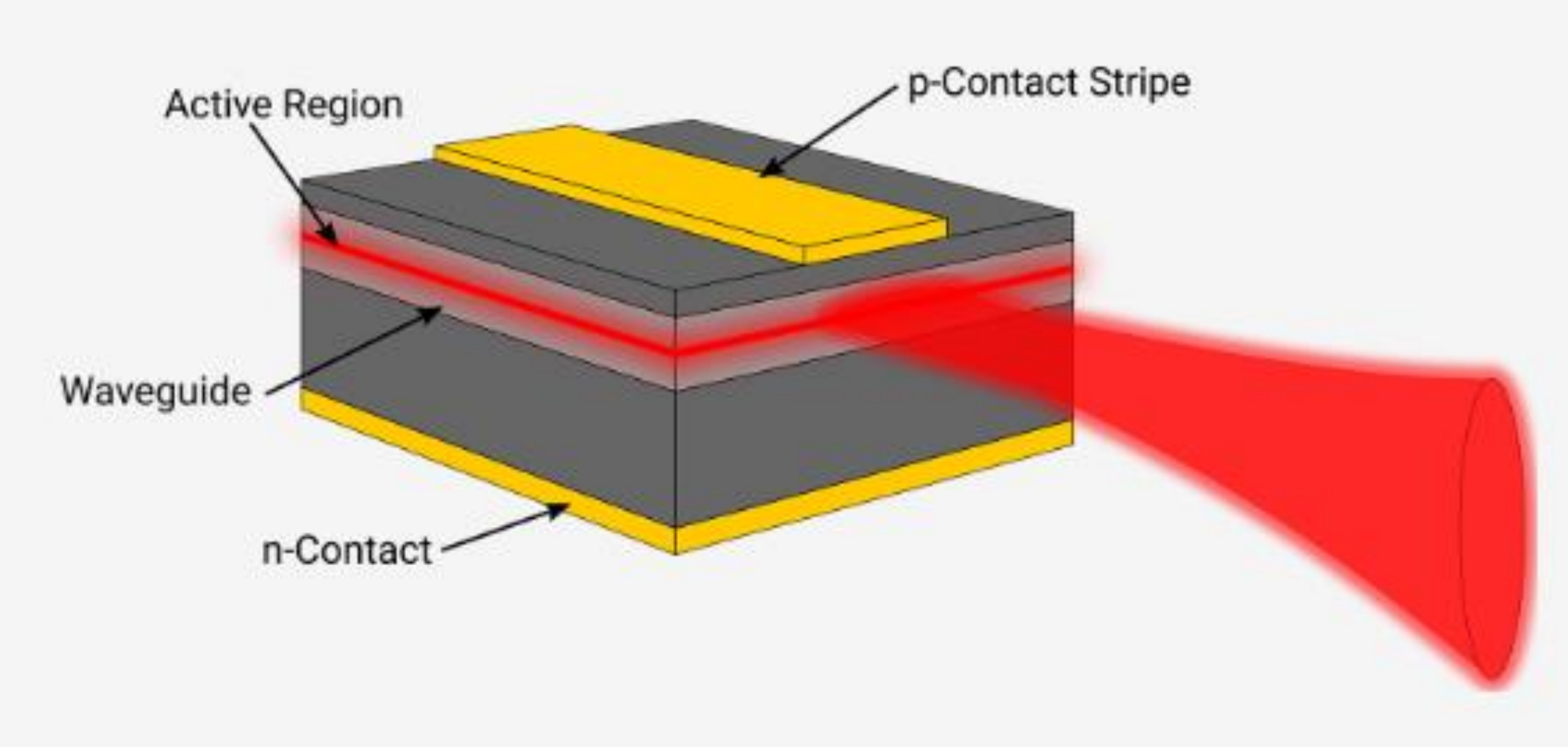
Modern Double Heterojunction Laser



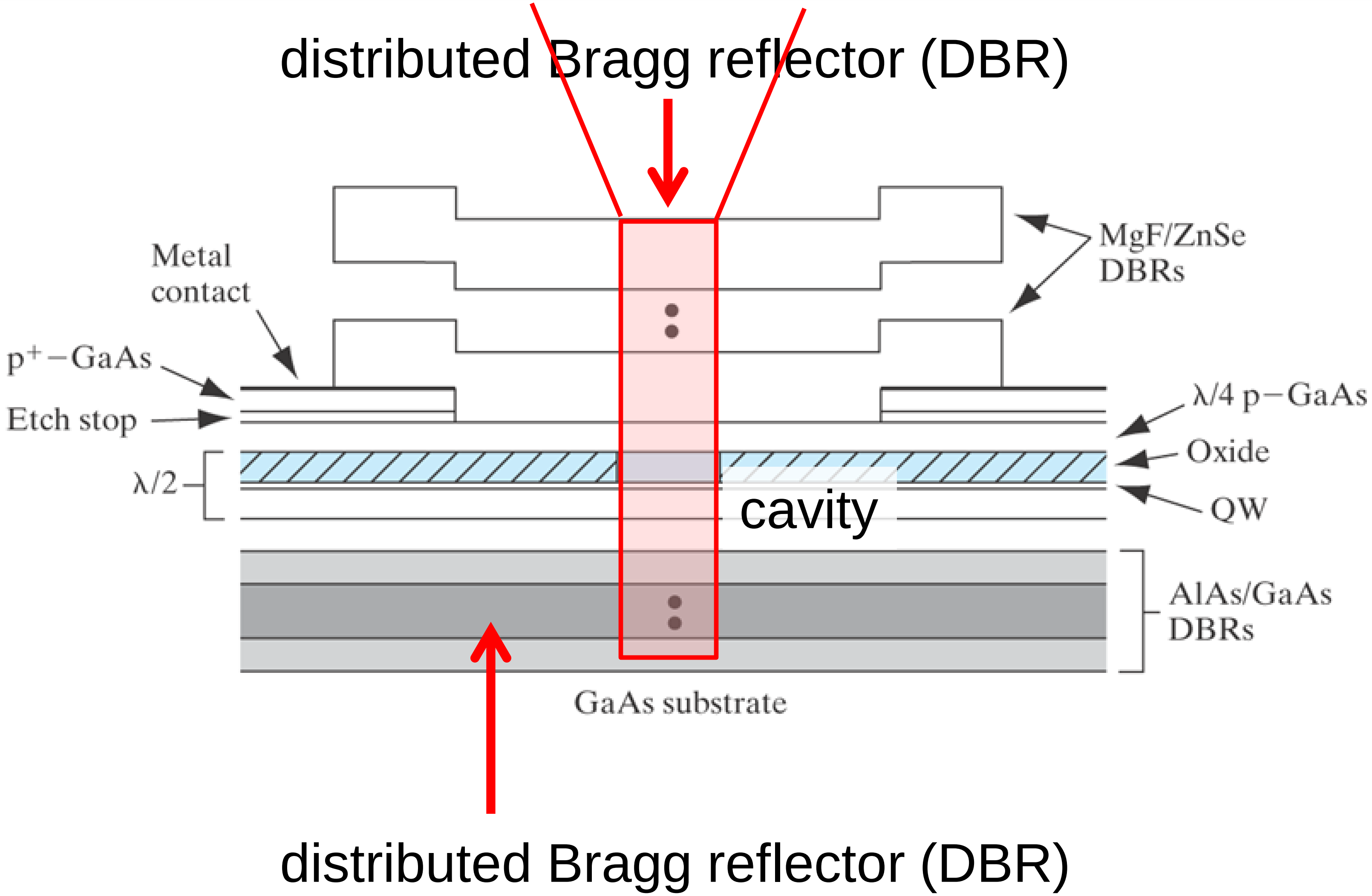
EDGE EMITTING LASER

Modern Double Heterojunction Laser



EDGE EMITTING LASER

Vertical Cavity Surface Emitting Laser (VCSEL)



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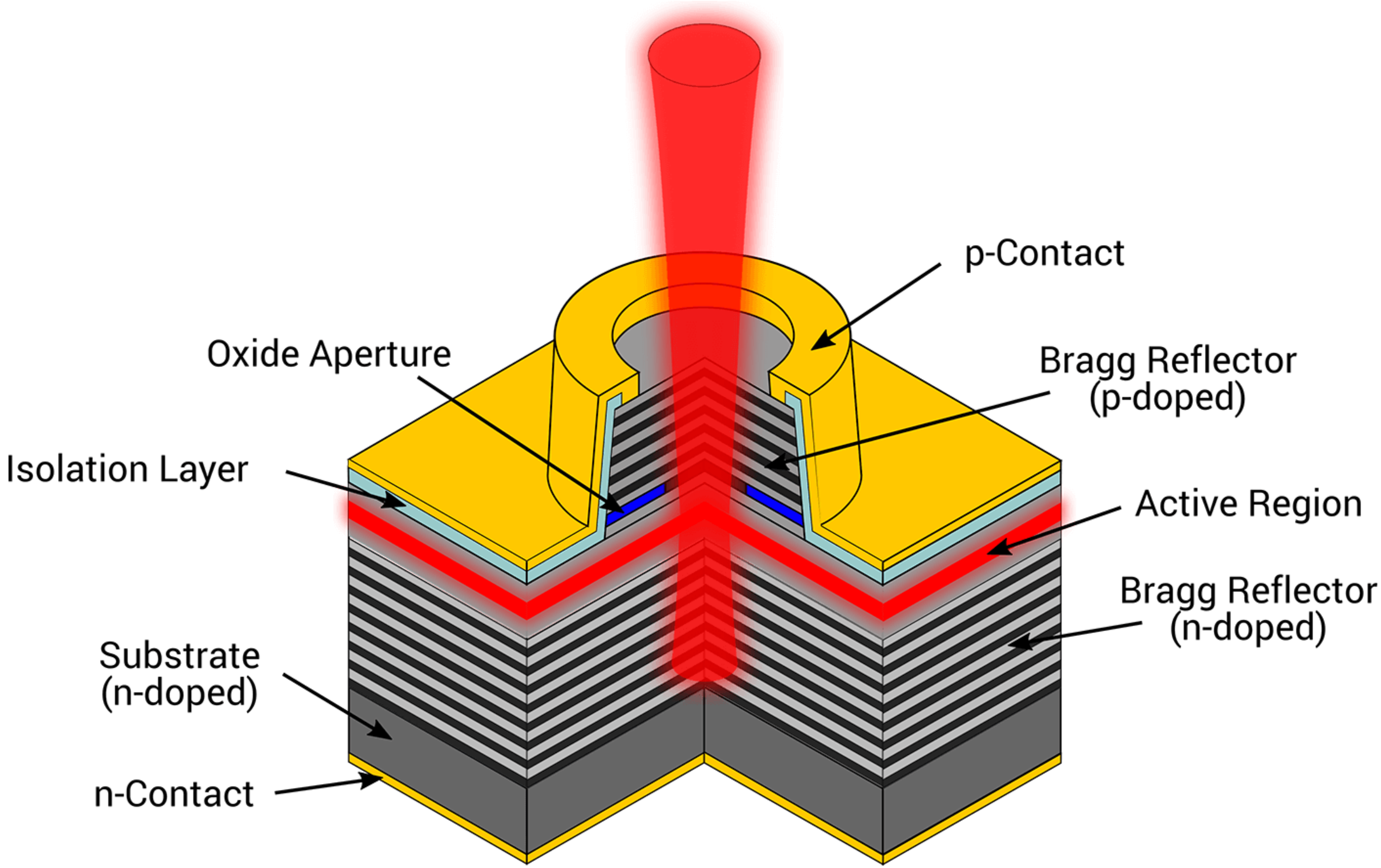

Reference: [Jetter, Roßbach, Michler (2013). Red Emitting VCSEL. In *VCSELs* (pp. 379-401). Springer Verlag]

Vertical Cavity Surface Emitting Laser (VCSEL)