ECE 340 Lectures 28
Solid State Electronic Devices

Spring 2022
10:00-10:50am

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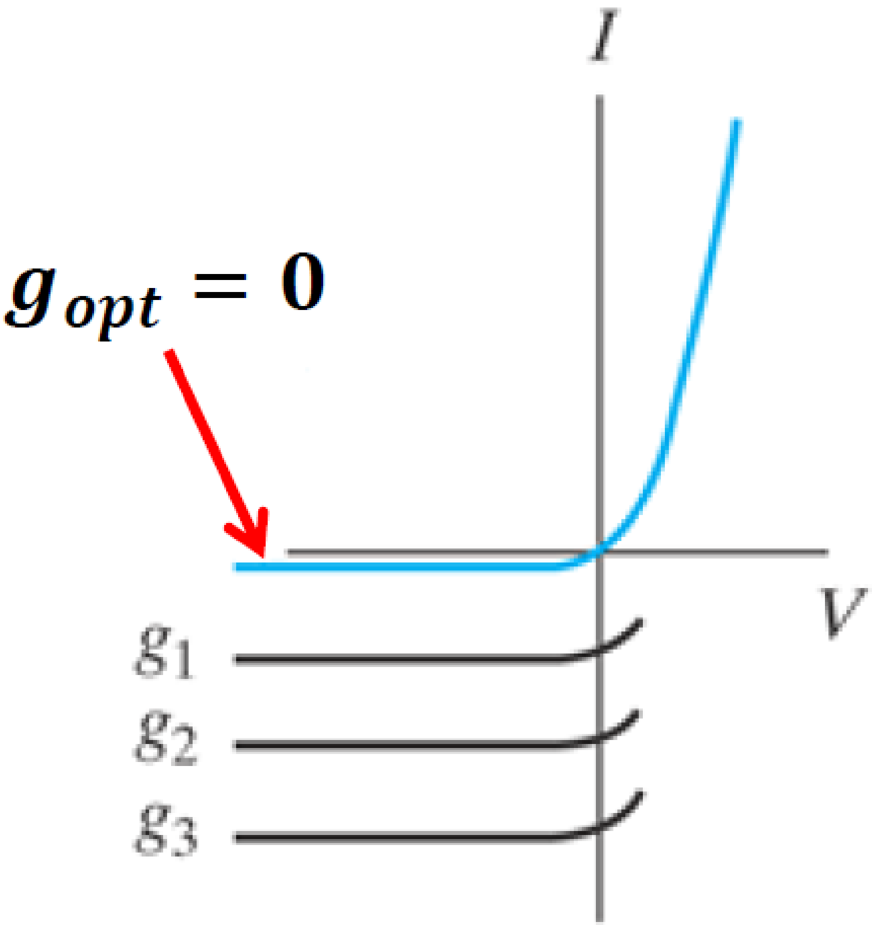
2062 ECE Building

Today's Discussion

- **Finish solar cells and photodetectors**
- **Semiconductor light emission**
- **LED (Light Emitting Diode)**
- **Semiconductor lasers**
- **Waveguiding in dielectric structures**

Photodiode – Photoconductive mode (reverse bias)

$$I = qA\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right] - qAg_{op}(L_p + L_n + W)$$

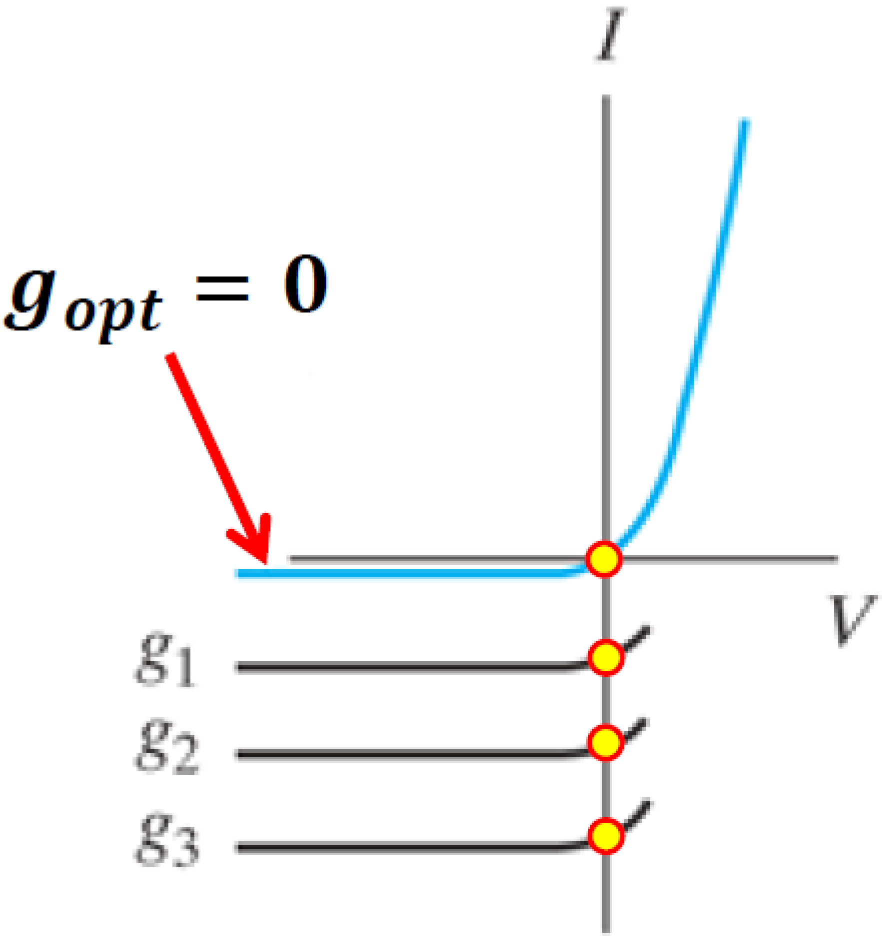


$$g_3 > g_2 > g_1$$

optical generation lowers the ***I*-*V*** curve

Photodiode – Photoconductive mode (reverse bias)

$$I = qA\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right] - qAg_{op}(L_p + L_n + W)$$



short circuit current

NOTE: V is the voltage at the ends of the diode, not the battery

Photodiode voltage – Photovoltaic mode

$$I = I_0\left[\exp\left(\frac{qV}{k_BT}\right) - 1\right] - I_{op} = 0 \Rightarrow V_{oc} = \frac{k_BT}{q}\ln\left(\frac{I_{op}}{I_0} + 1\right) \Rightarrow$$

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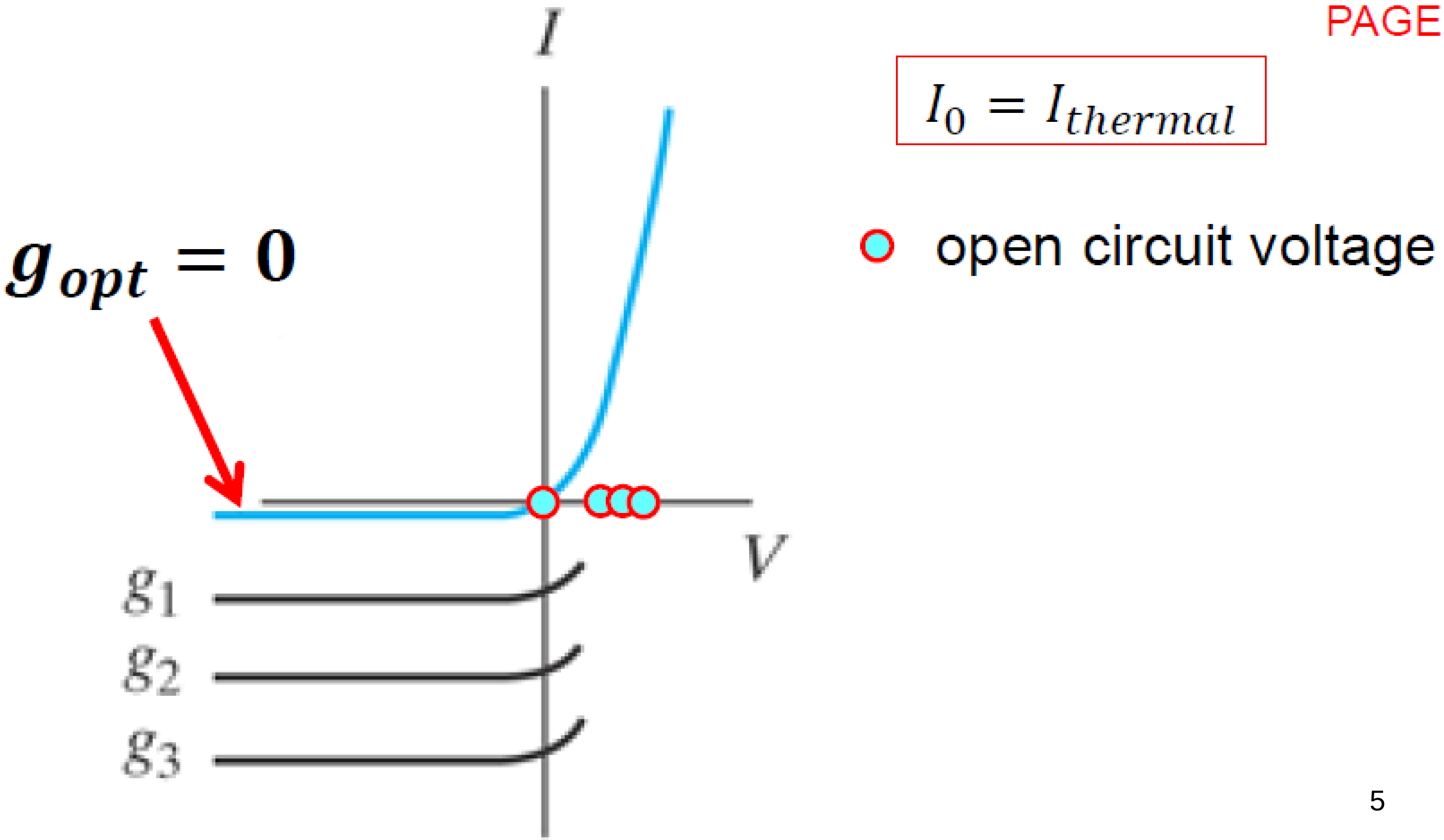
$$I_0 = I_{thermal}$$



Photodiode voltage

open circuit voltage

$$V_{oc} = \frac{k_B T}{q} \ln\left(\frac{I_{op}}{I_0} + 1\right) =$$

$$= \frac{k_B T}{q} \ln\left(\frac{L_p + L_n + W}{\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p} g_{op} + 1\right)$$

Photodiode voltage

open circuit voltage – symmetrical junction

$$p_n = n_p;\ \tau_n = \tau_p; \quad g_{th} = \frac{p_n}{\tau_n}$$

$$V_{oc} = \frac{k_B T}{q} \ln\left(\frac{L_p + L_n + W}{\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p} g_{op} + 1\right)$$

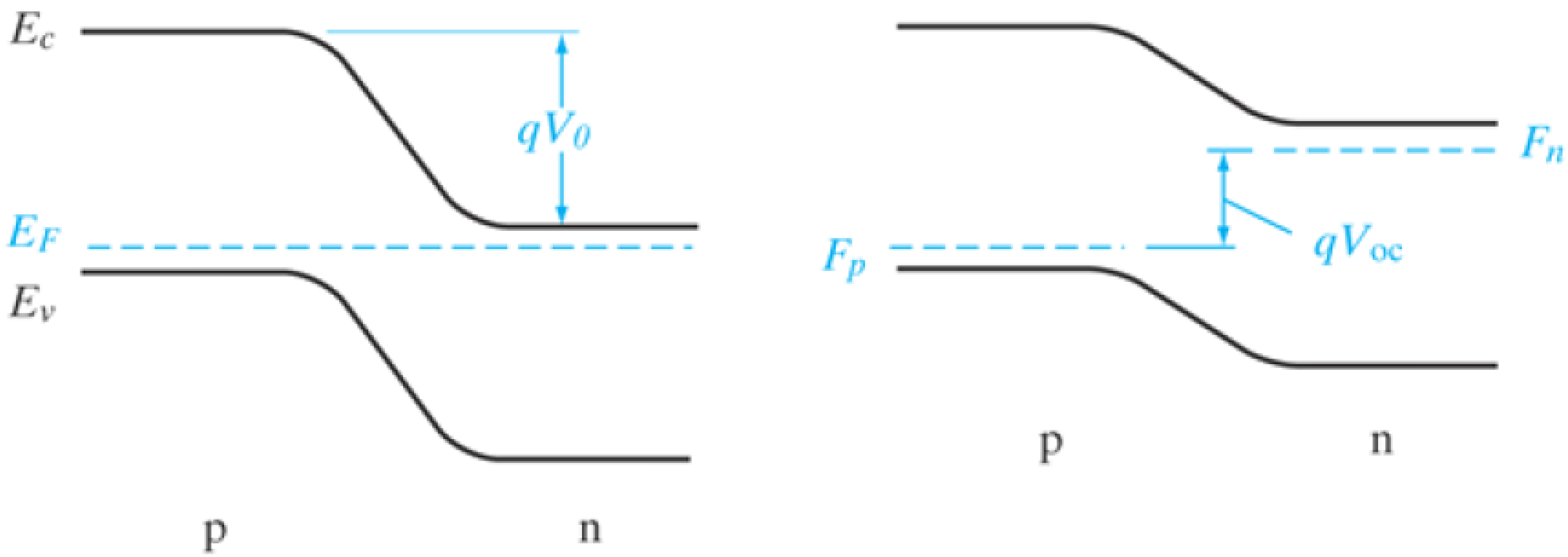
if generation inside
W can be neglected

If $g_{op} \gg g_{th}$

$$V_{oc} = \frac{k_B T}{q} \ln\left(\frac{L_p + L_n + \cancel{W}}{(L_p + L_n) g_{th}} g_{op} + 1\right) = \frac{k_B T}{q} \ln\left(\frac{g_{op}}{g_{th}} + \cancel{1}\right)$$

Open circuit voltage

Fermi level splits into quasi-Fermi levels

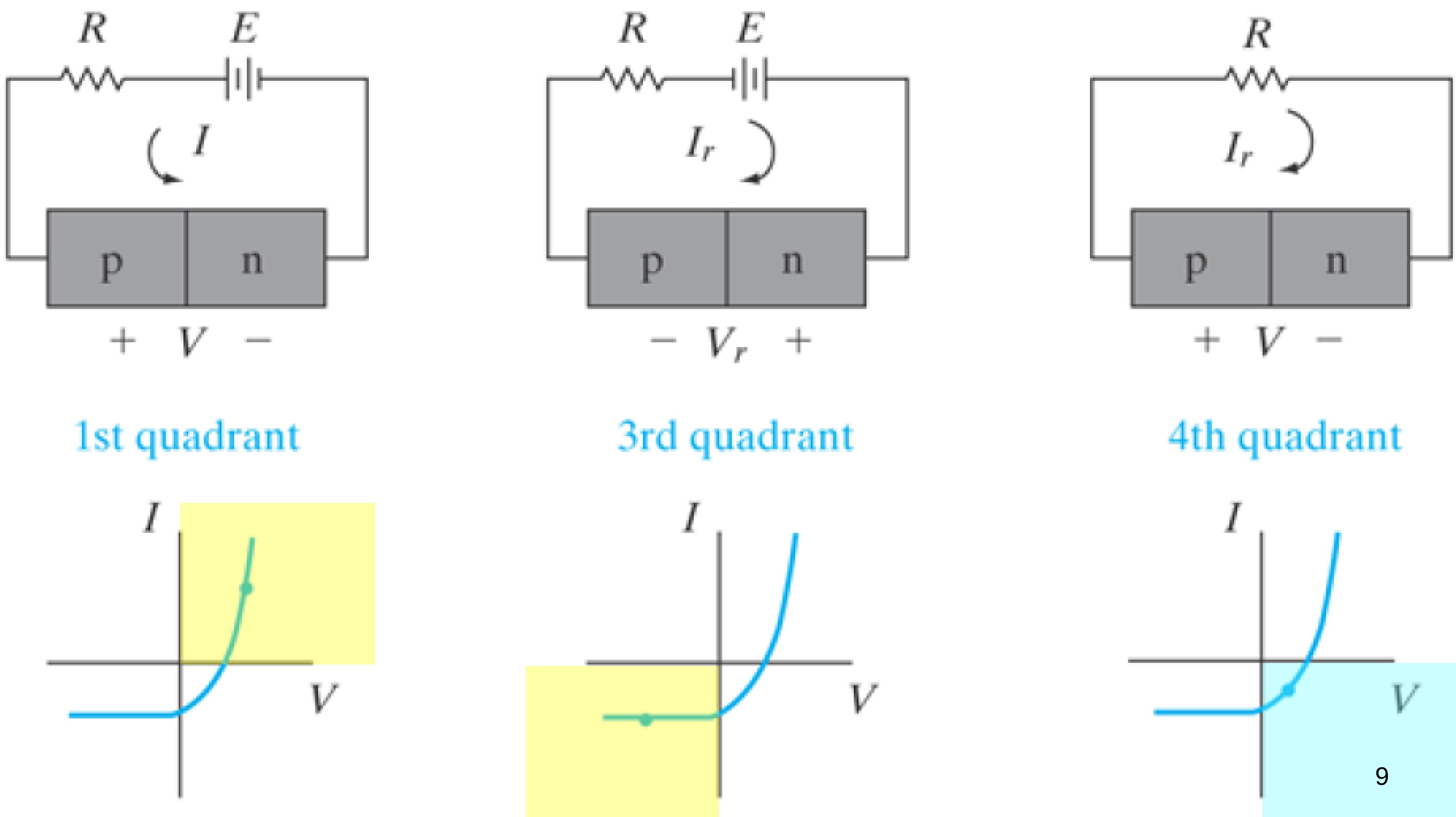


Limit to qV_{oc} is the contact potential qV_o

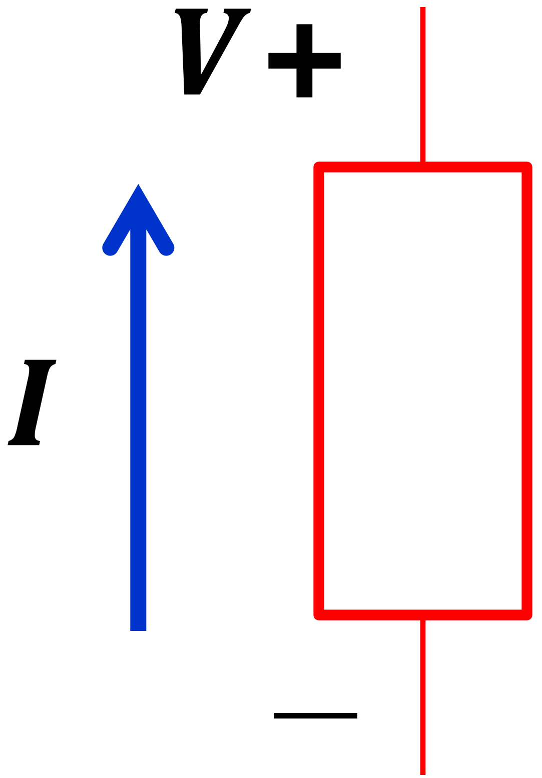
Operation of illuminated junction

power delivered to junction by external circuit

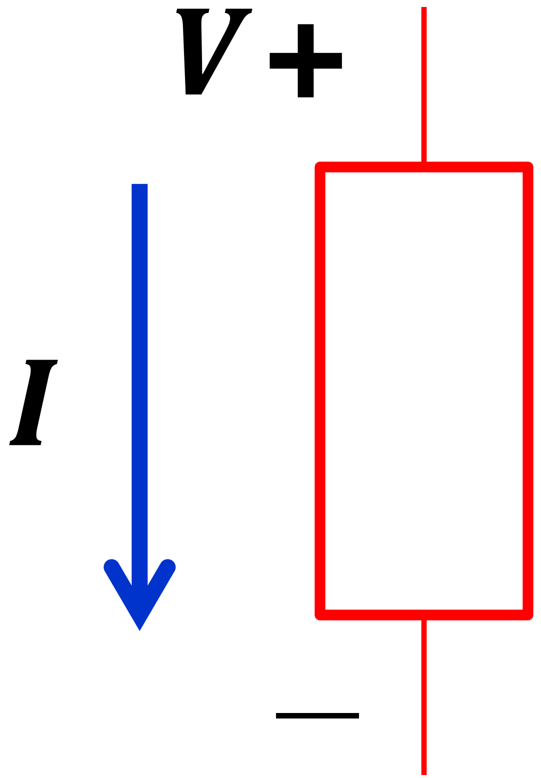
power delivered to load by junction



Remember:

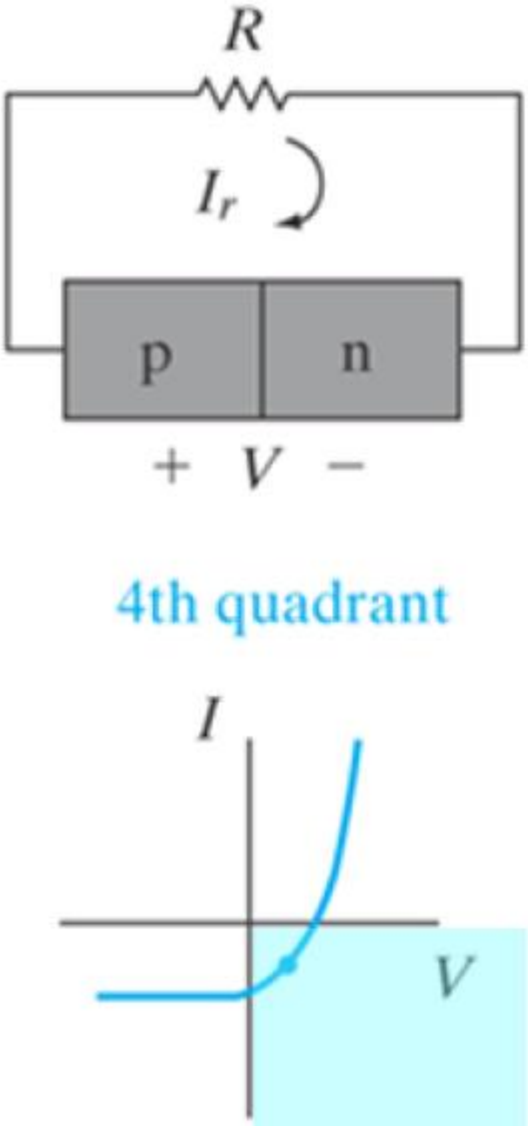


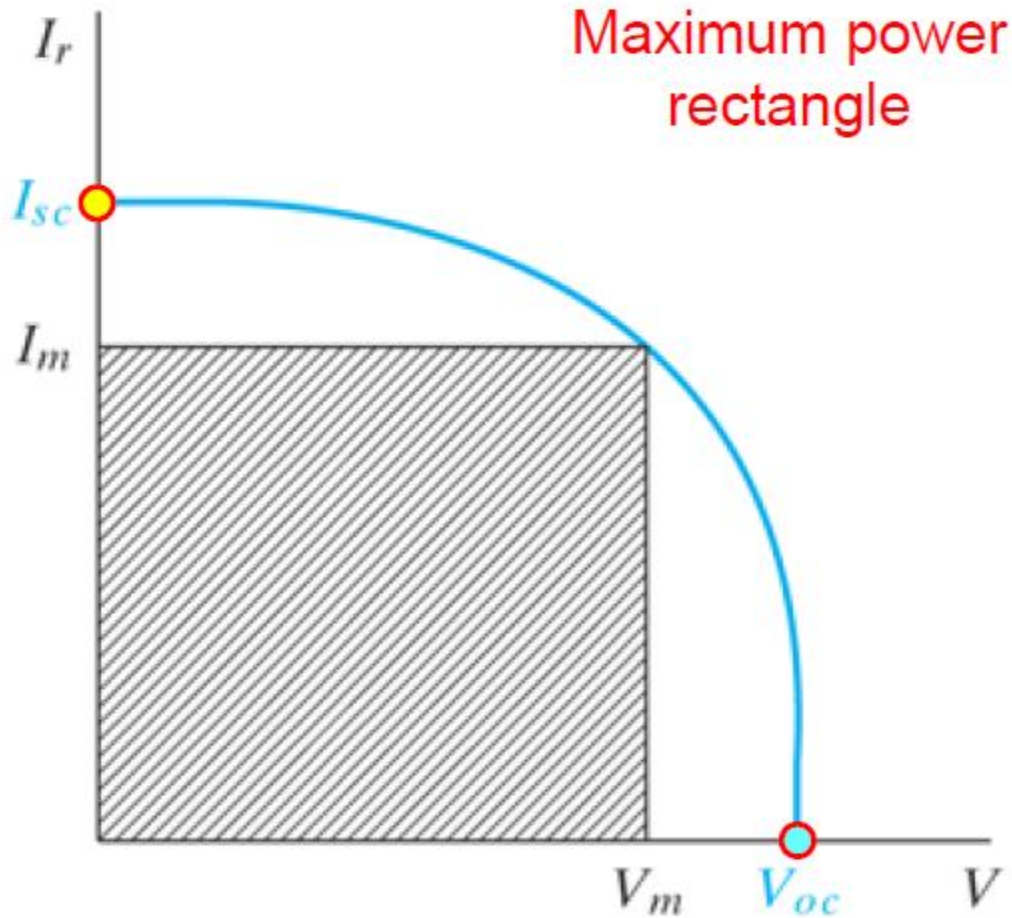
Element provides power (source)



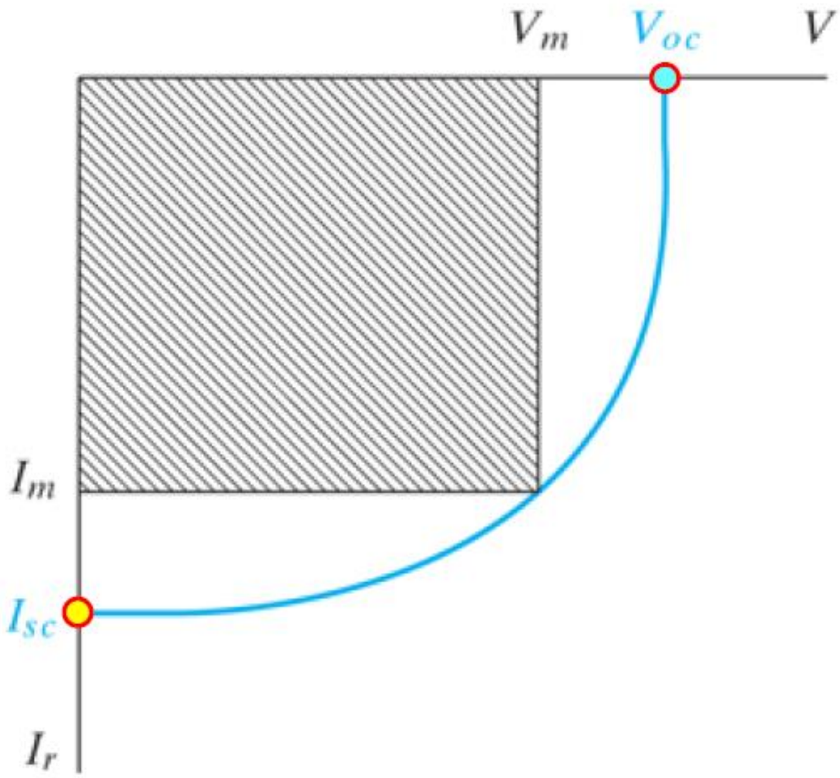
Element consumes power (e.g., resistive)

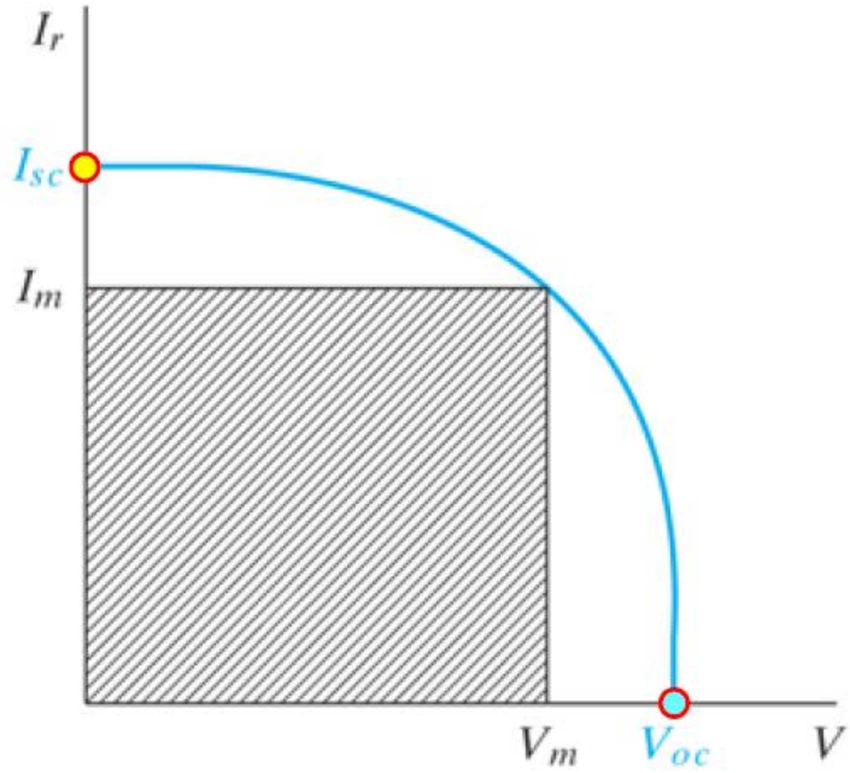
Solar cell – photovoltaic mode



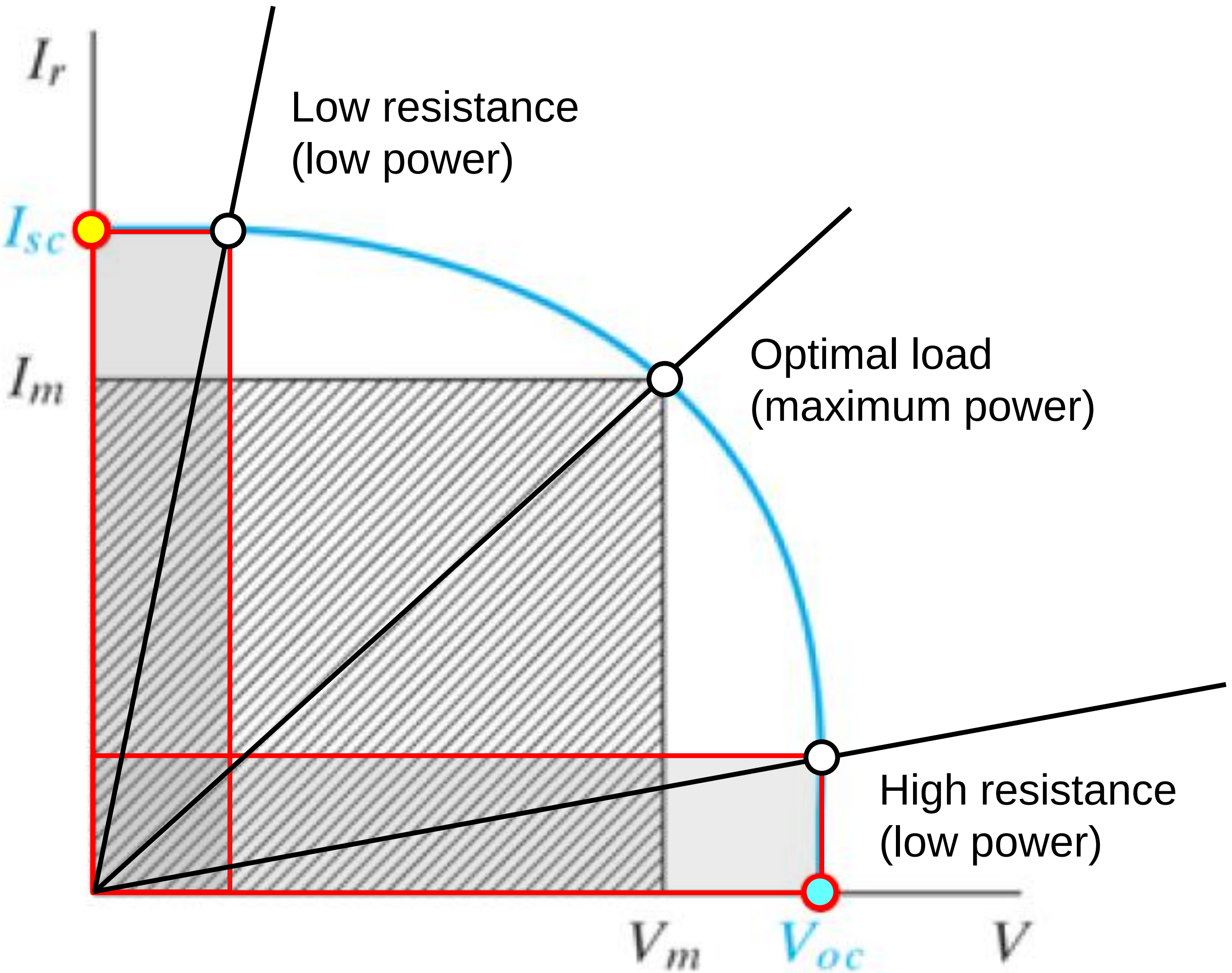


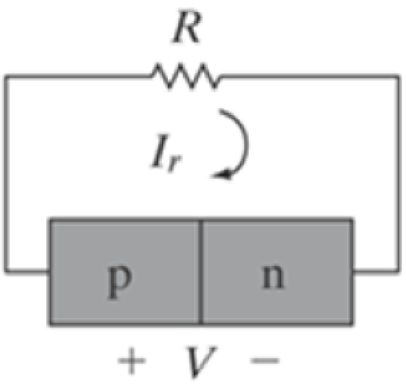
NOTE: you may find this diagram plotted either way





Maximum power requires optimal load





Solar cell - Example

A solar cell has short-circuit current of 100 mA and open circuit voltage of 0.8 V under full solar illumination. With a fill-factor 0.7 what is the maximum power delivered to a load by the cell?

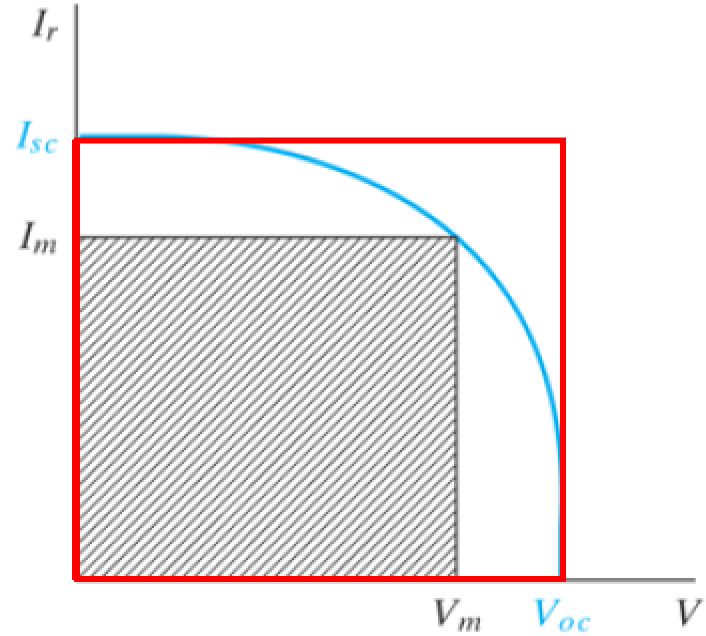
$$\frac{V_M \times I_M}{V_{oc} \times I_{sc}} = \text{Fill Factor}$$

$$P_{max} = V_M \times I_M =$$

$$= (V_{oc} \times I_{sc}) \times \text{Fill Factor}$$

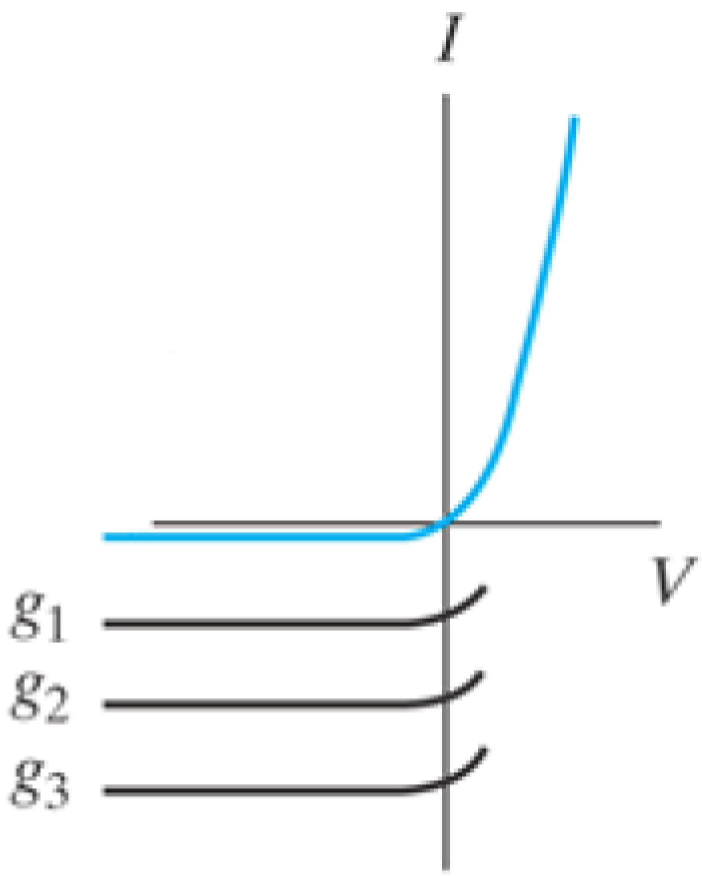
$$= (0.8 \times 100m) \times 0.7$$

$$= 0.056W = 56mW$$



Photodetectors

When operated in third quadrant, the current through the photodiode is essentially independent of voltage and proportional to the optical generation rate.



If we want to use the photodiode to detect optical communications then speed of generated carrier collection is important to have large bandwidth.

(Larger bandwith = more customers accommodated in the same channel)

Photodetectors

Carrier diffusion is a slow process.

Best situation if most of the carriers are generated in the high-field depletion region (depletion layer photodiode)

Wide depletion layer = High sensitivity

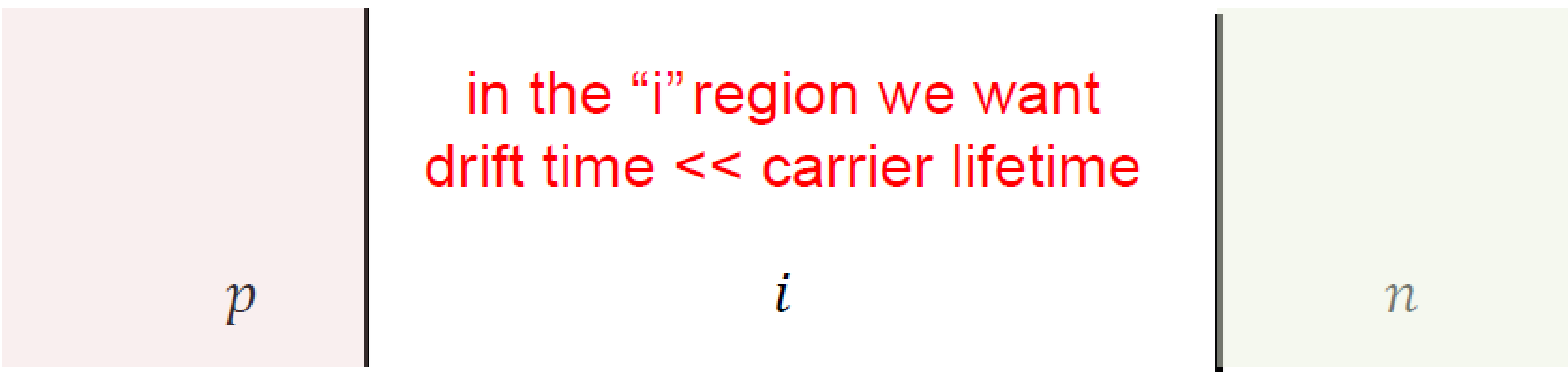
ADVANTAGE: A wide junction has lower capacitance (remember the previous lecture?). Good for RC constant and speed.

POTENTIAL DRAWBACK: If the depletion region is too wide, it may take too long for carriers to traverse it, which may affect adversely the bandwidth.

p-i-n photodetector

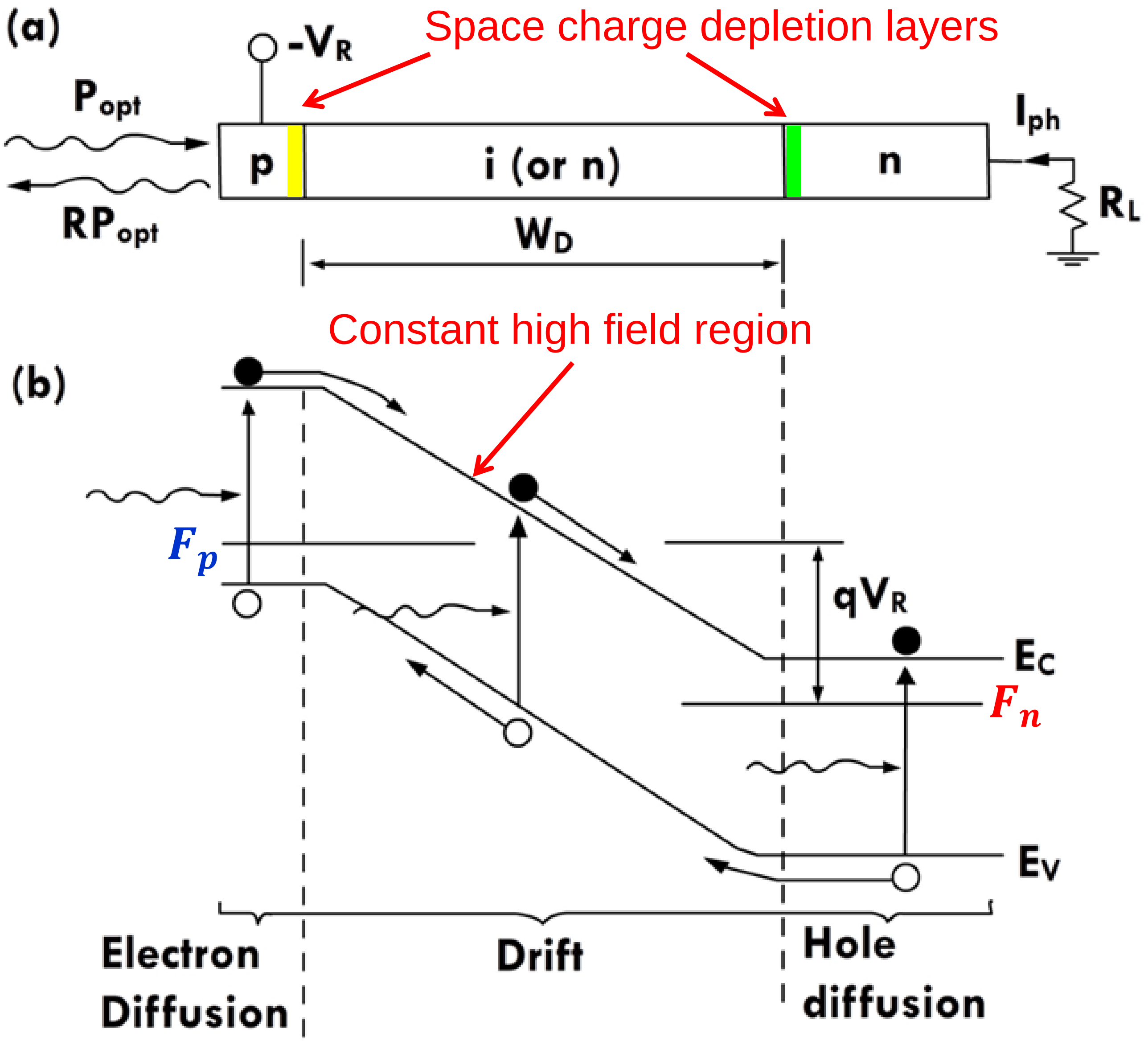
A low doped region is sandwiched between *p* and *n* sides (the “i” stands for intrinsic. There may be some doping but important thing is to have a high resistivity).

In reverse bias, most of the voltage drops across the high resistivity “i” region.



so most carriers generated are collected by the *p* and *n* regions

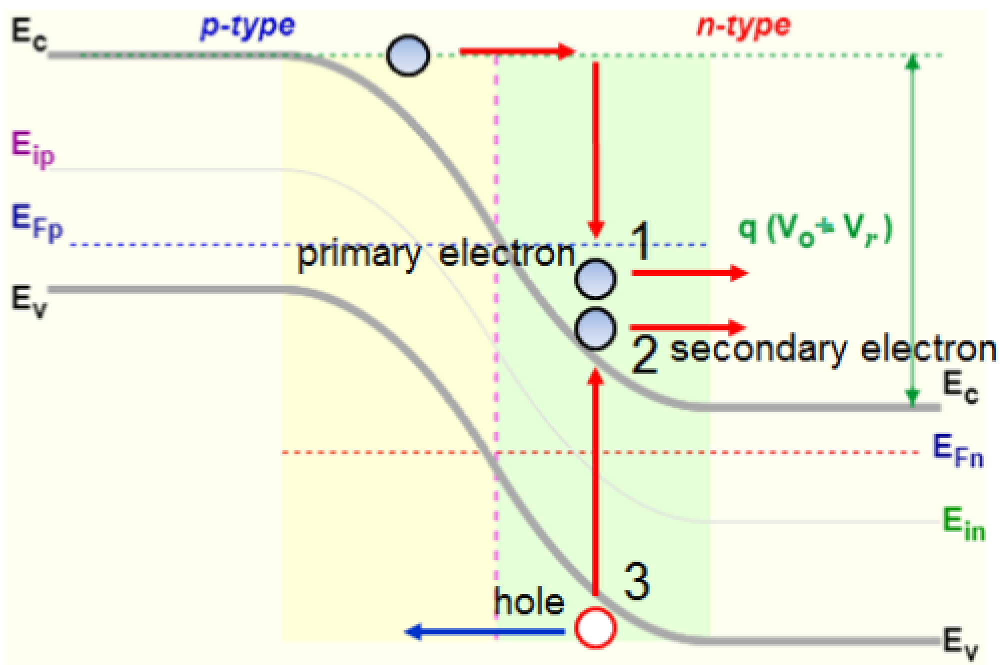
p-i-n photodetector



Avalanche Photodiode (APD)

Consists of a p-n junction in reverse bias operated in *breakdown conditions*.

Each photogenerated carrier has the chance to generate EHP by impact ionization. By avalanche multiplication, the signal is essentially amplified.



Avalanche Photodiode (APD)

APD's are very sensitive, but noise can be a problem because of the randomness of the generation by impact ionization process.

The bandgap of the material is tailored to the optical frequencies to be detected so that generated carriers have similar energies. Creation of the material system follows *bandgap engineering* design procedures, using compound III-V semiconductors.

APD's are very useful for long distance optical fiber communication systems.

Quantum Efficiency

This is an important figure of merit of photodetectors:

How many carriers are collected per incoming photon of energy $h\nu$?

$$\frac{Photocurrent\ density}{electron\ charge} = \frac{J_{op}}{q} = \#\ carriers/\text{s}$$

$$\frac{Incident\ optical\ power\ density}{energy\ of\ a\ photon} = \frac{P_{op}}{h\nu} = \#\ photons/\text{s}$$

$$\eta_Q = \frac{J_{op}}{q} \Big/ \frac{P_{op}}{h\nu} = quantum\ efficiency$$

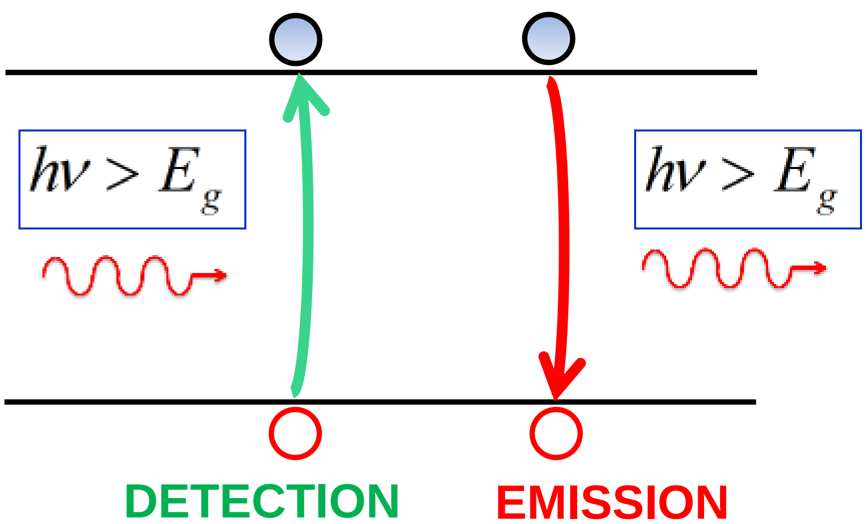
Devices based on light emission

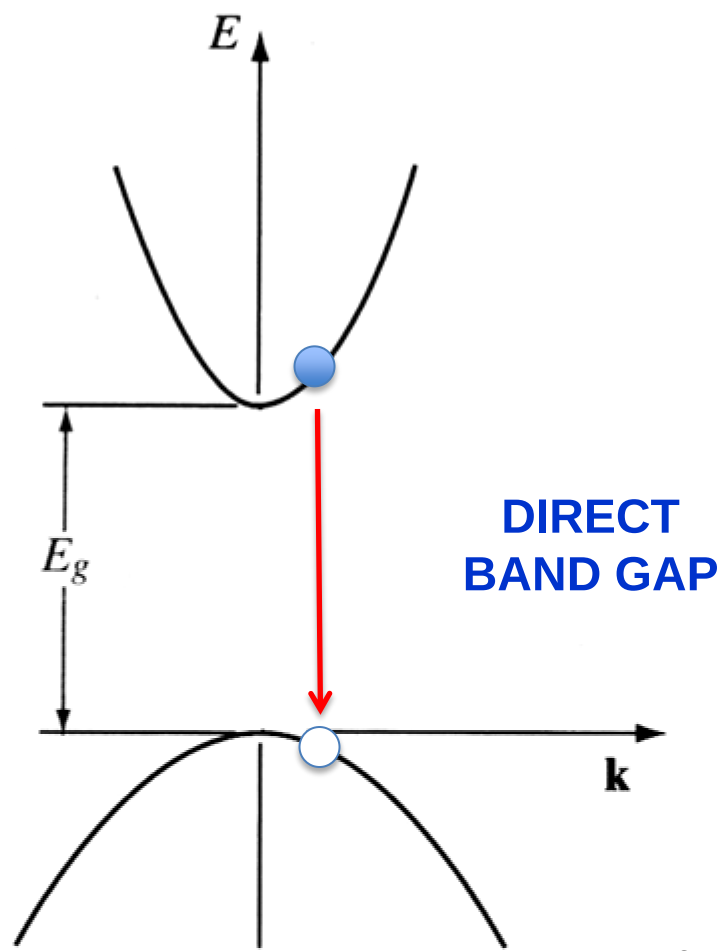
Light Emitting Diode (LED)

Semiconductor Laser

Light emission in semiconductor material

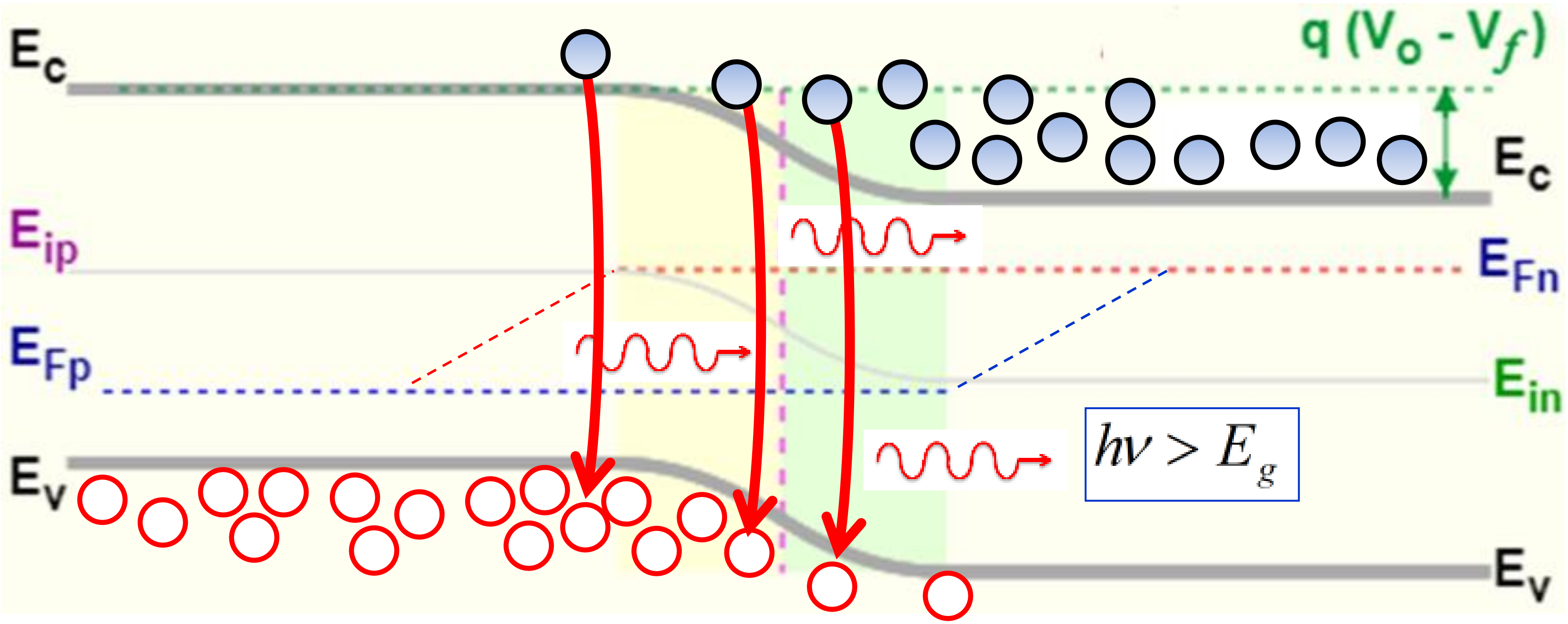
- **Light emission is the reverse process of light detection**





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

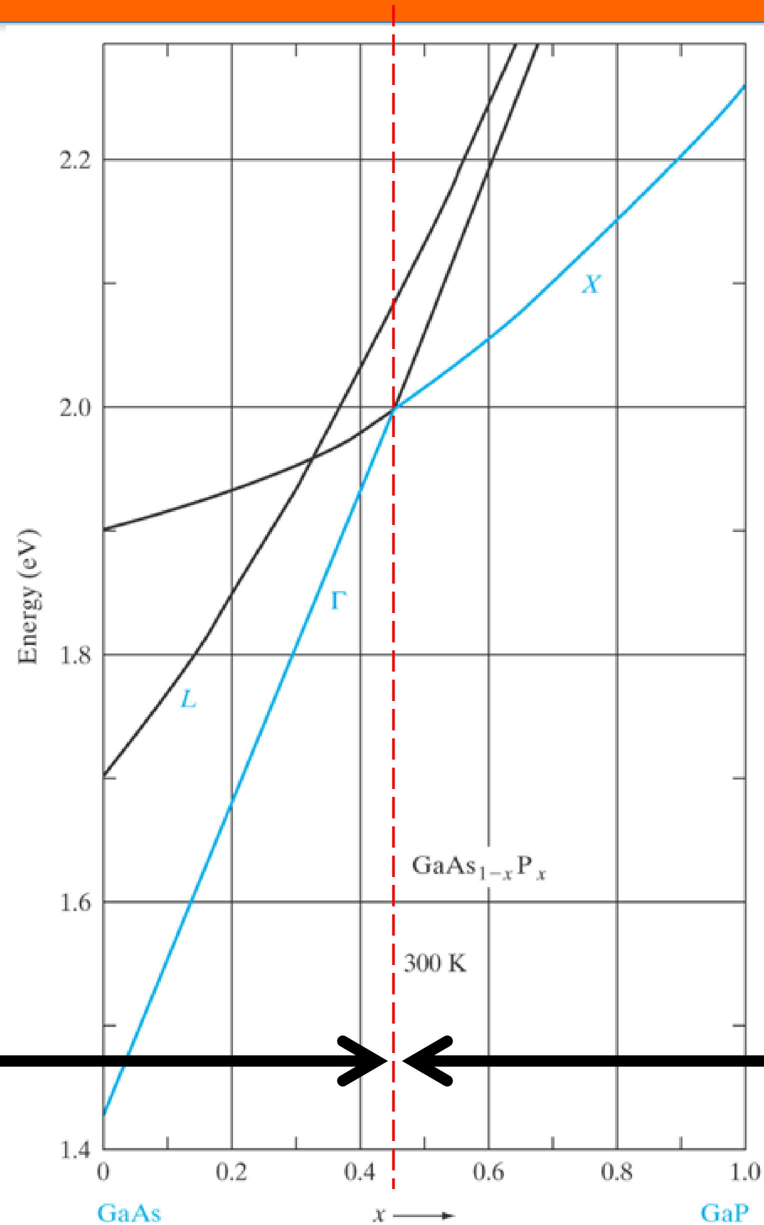
A very important LED material: $GaAs_{1-x}P_x$

- $GaAs_{1-x}P_x$ alloy

Valley minima in momentum space

Γ = direct

L & X = indirect



DIRECT BAND GAP

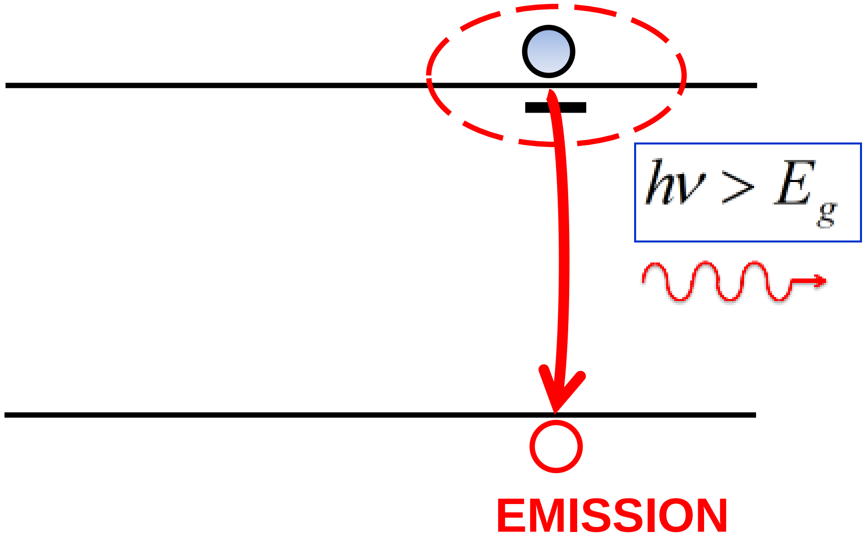
$x < 0.45$

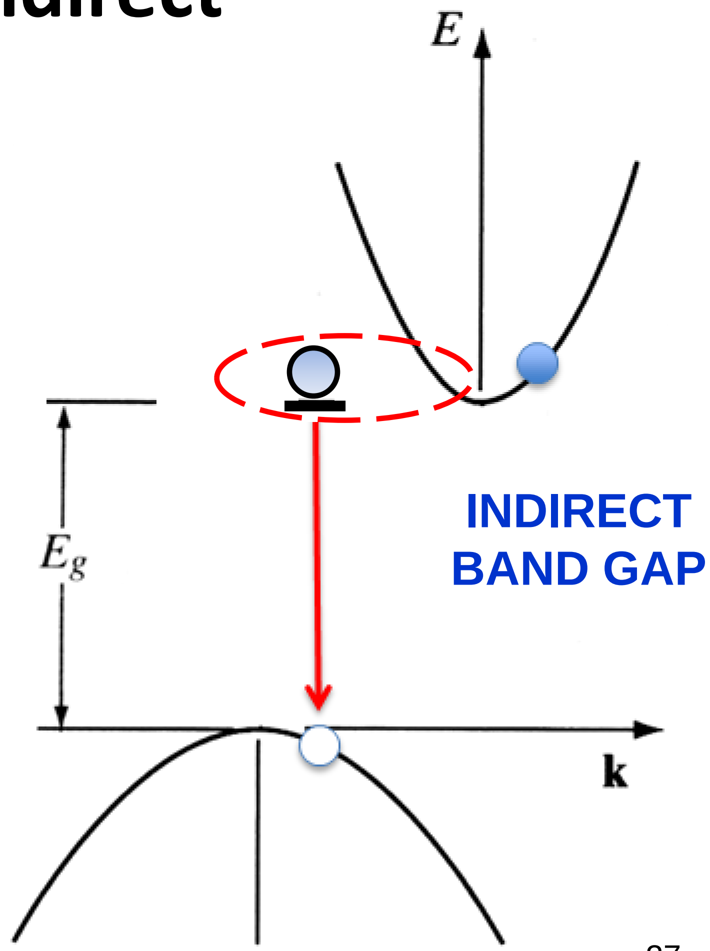
INDIRECT BAND GAP

$x > 0.45$

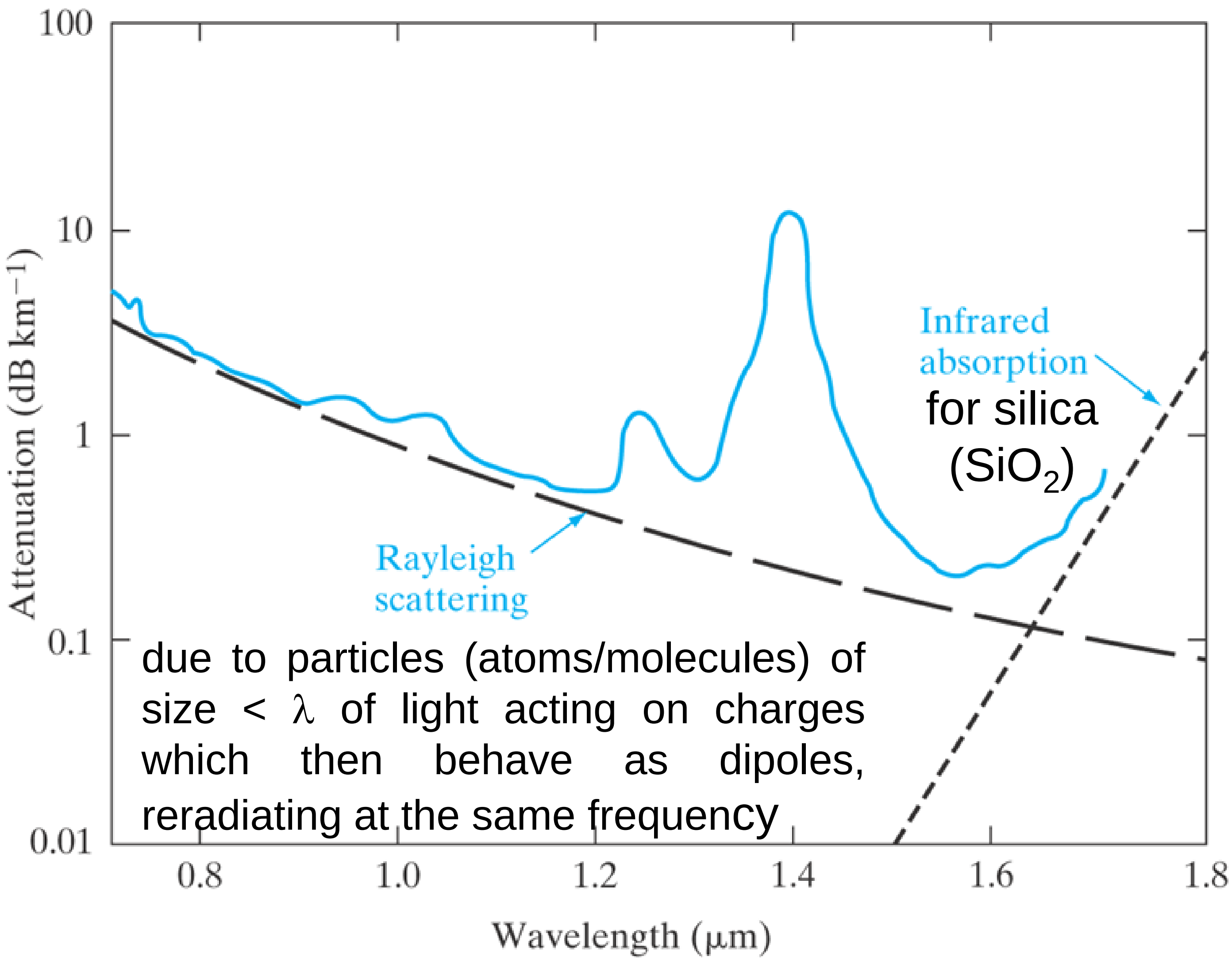
Emission in indirect material: $GaAs_{1-x}P_x$

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



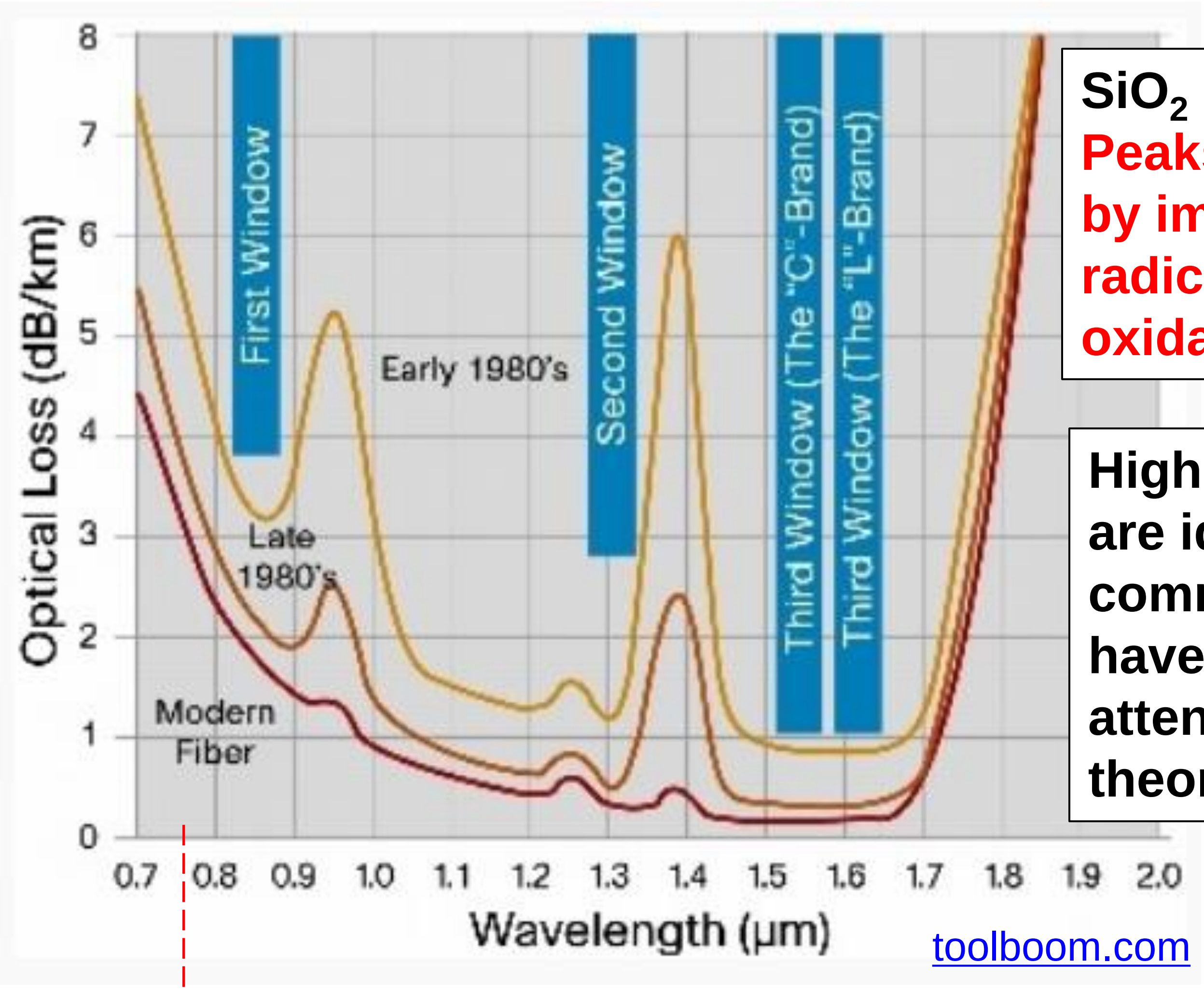


Fiber optics: Why infrared light?



Fiber optics communications

- **Commercial links started in 1984**



toolboom.com

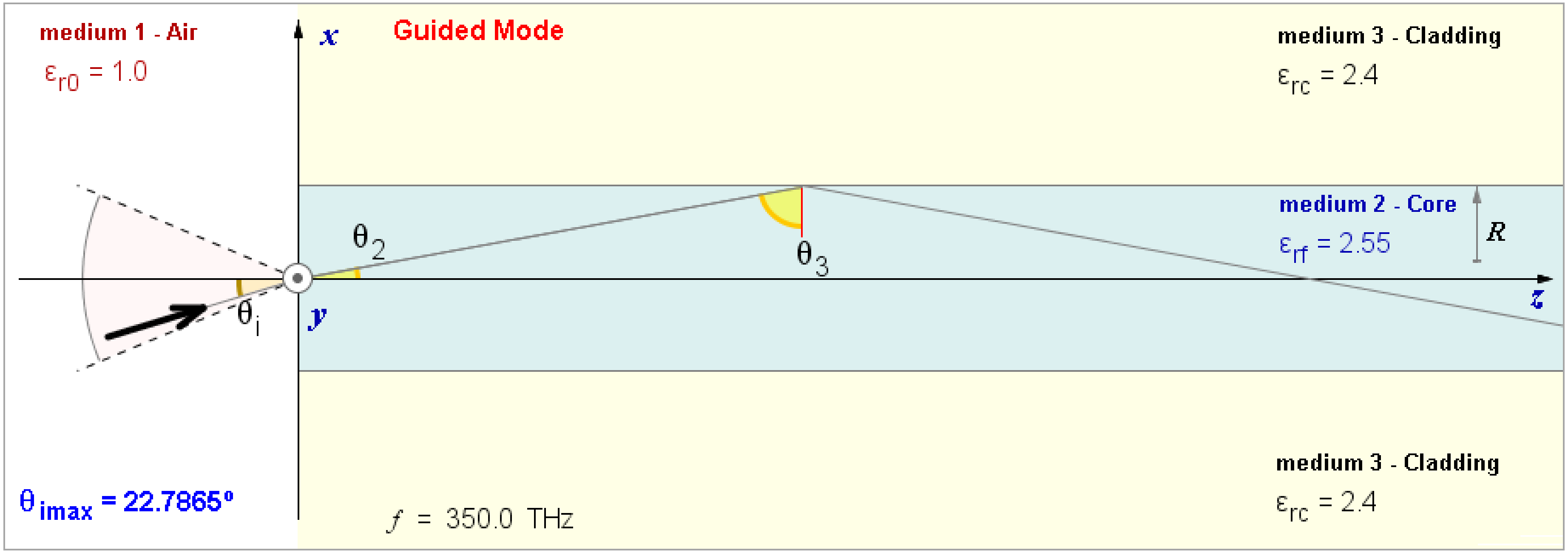
SiO_2 (glass) fibers
Peaks are due to absorption by impurities, mainly OH^- radicals, released during oxidation process.

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?

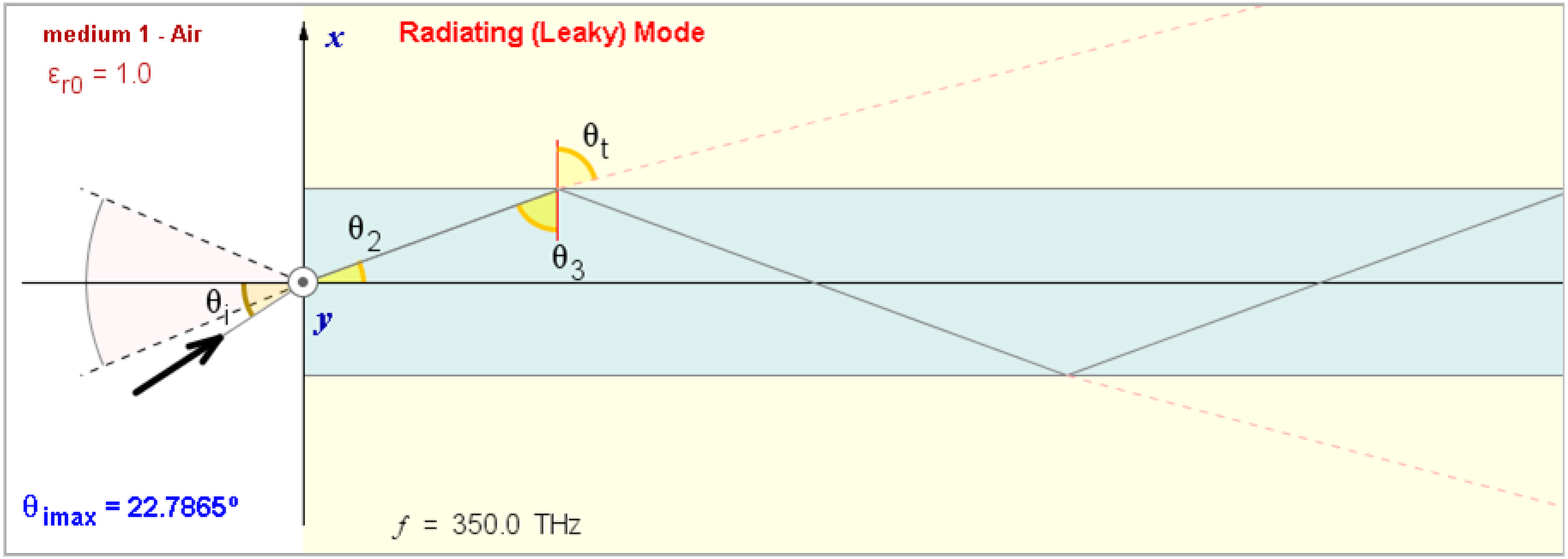
- **Total internal reflection at the interface between core and cladding**



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?

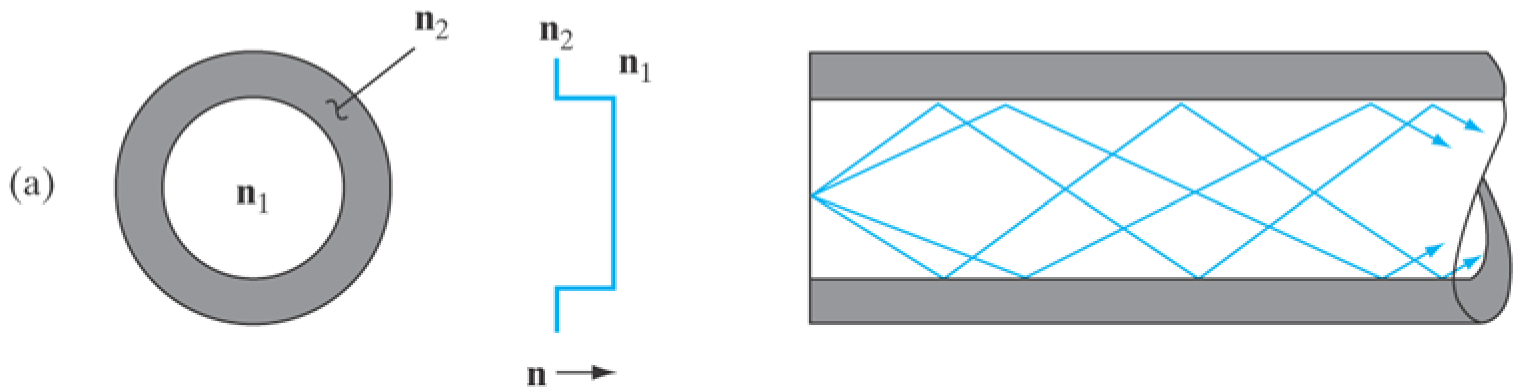
- **Entrance beyond the maximum angle causes radiation into the cladding (loss of power)**



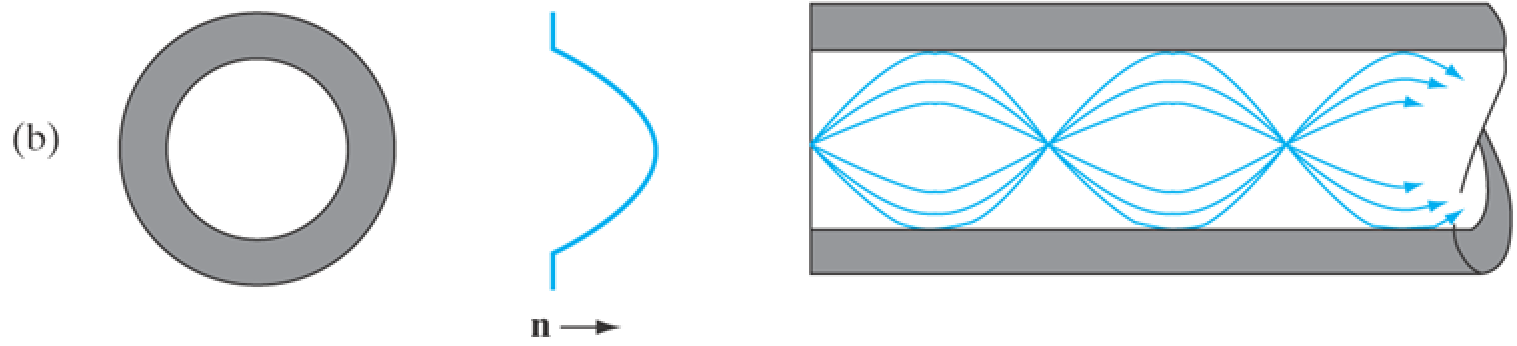
modes are leaky and dissipate quickly along length of fiber

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

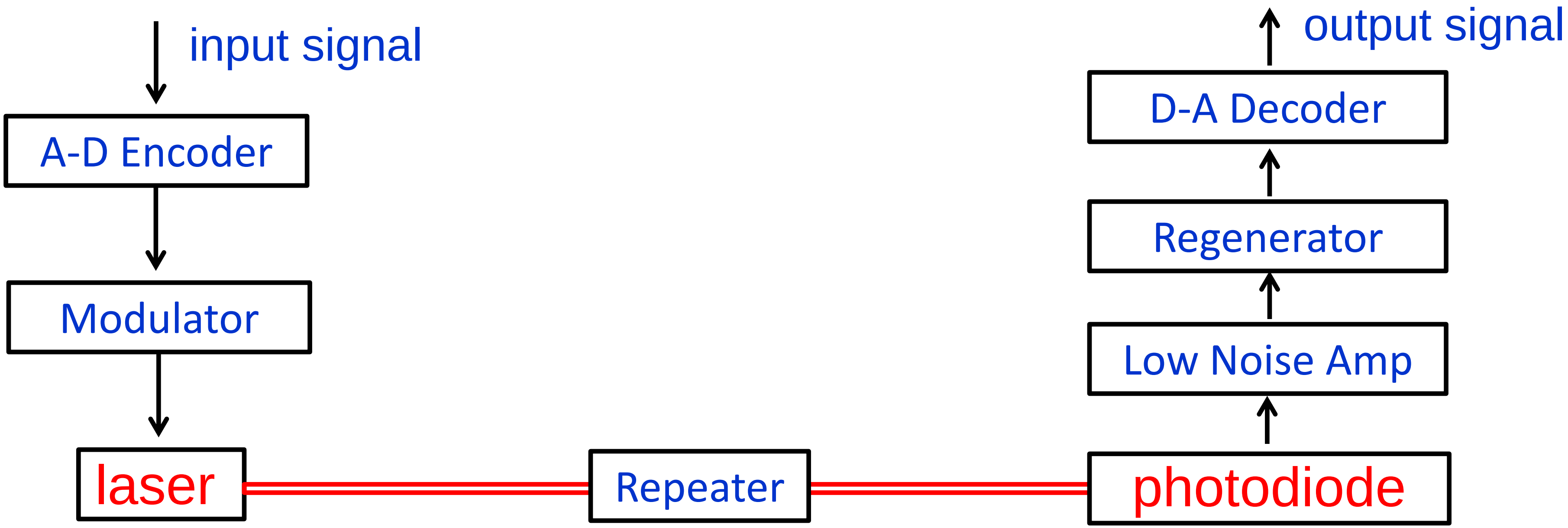
- **Monomode fiber –** It has narrow core diameter (8 μm or 10.5 μm) and it allows only axial propagation. In single mode there is no appreciable dispersion so bandwidth (or length of communication link) can be much greater.
- It uses higher performance quantum well lasers (1.3 μm or 1.55 μm) and very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

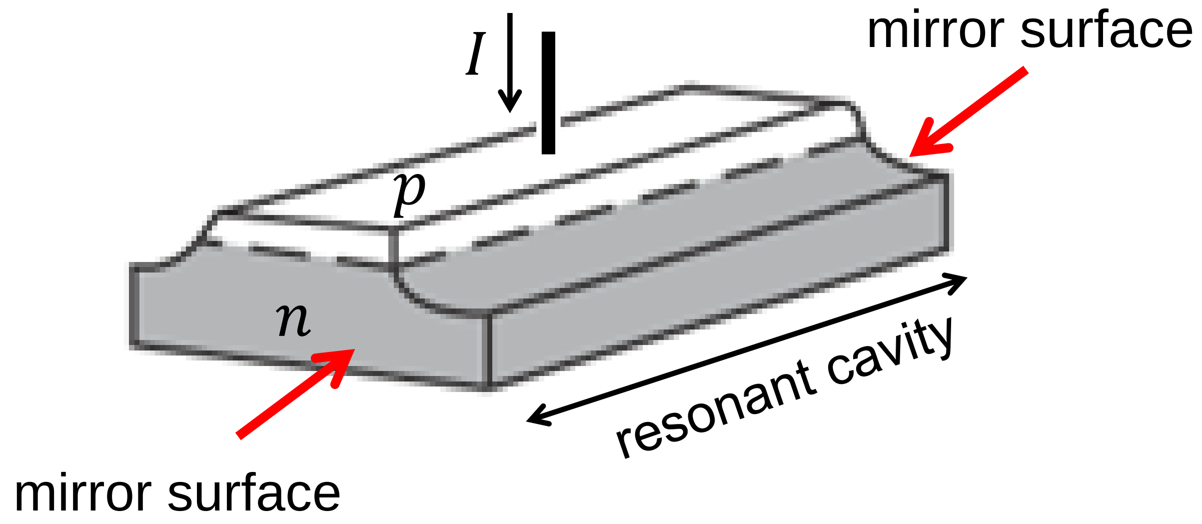
Stimulated

Emission of

Radiation

Semiconductor Laser

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

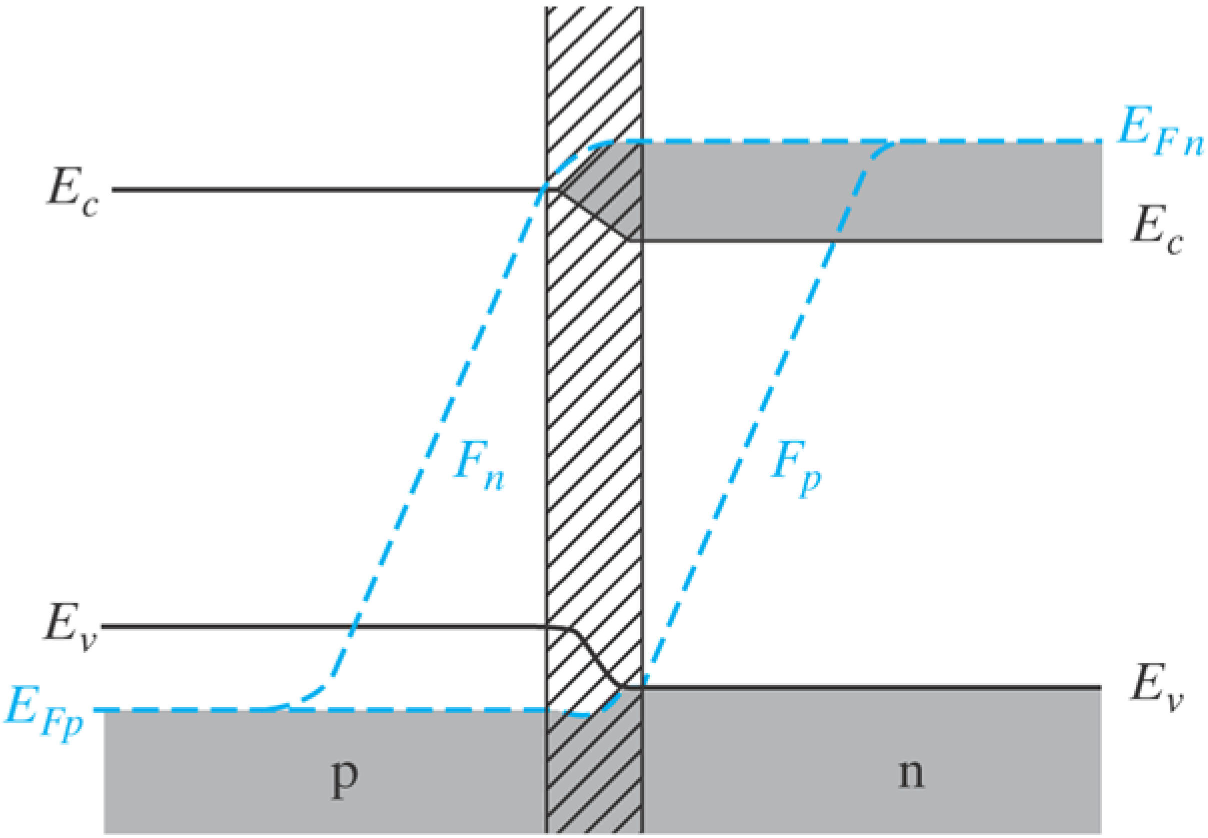


Two ingredients are needed to make a laser:

- 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**



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

Population Inversion

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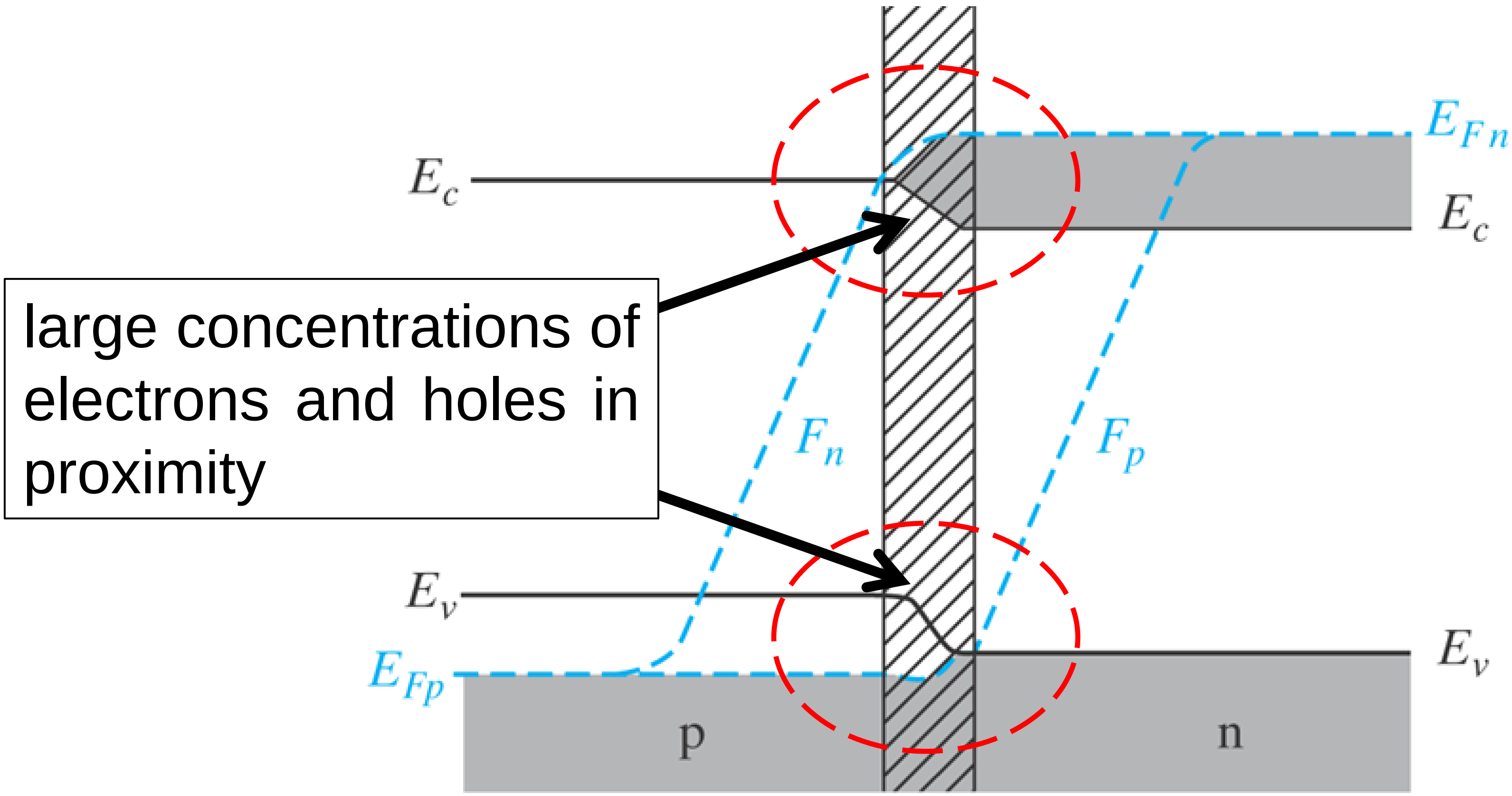

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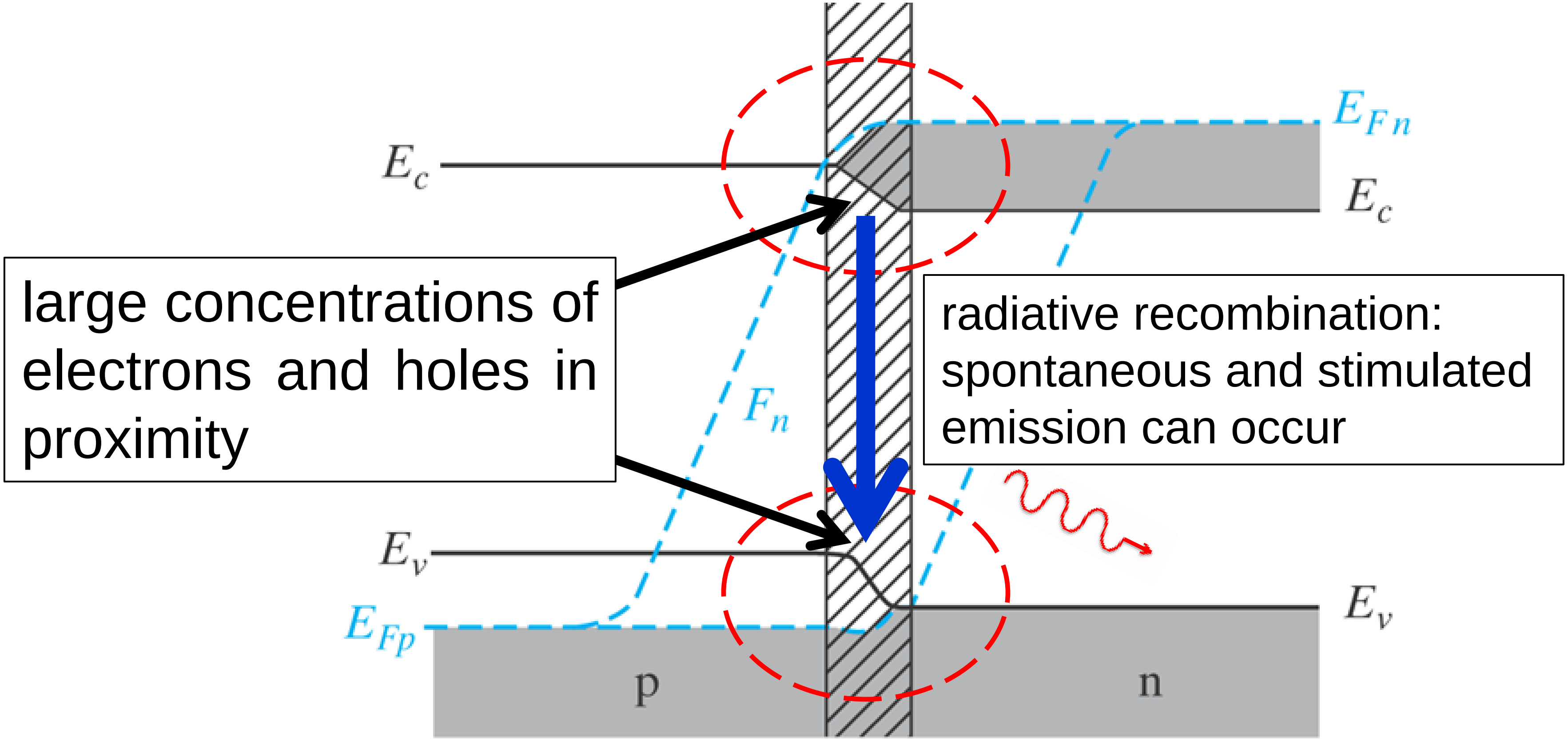

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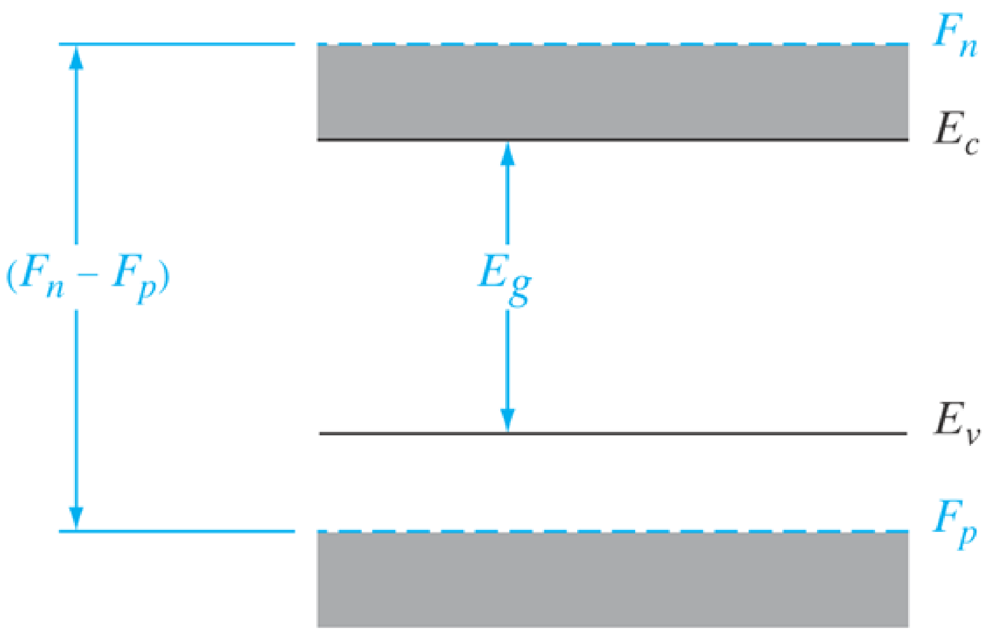
Population inversion

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

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



electrons can recombine approximately in the range of energies

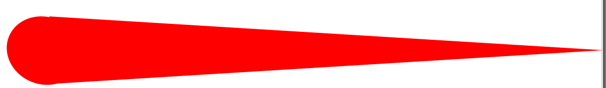
$$E_g < h\nu < (F_n - F_p)$$

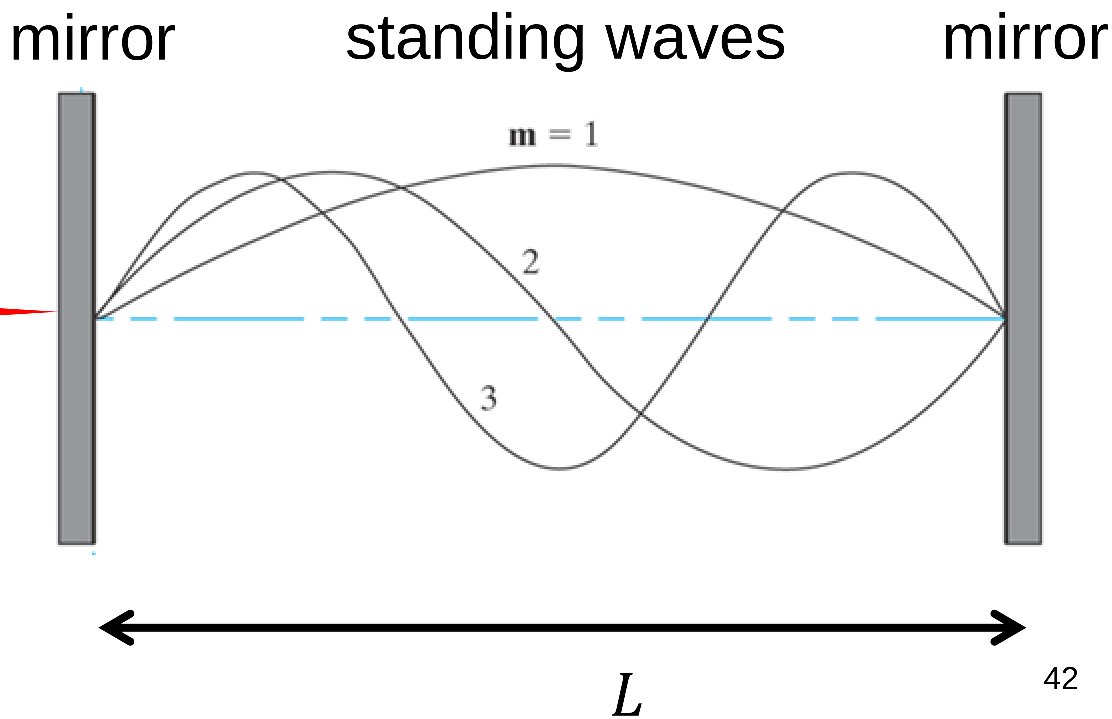
Cavity modes

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

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

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

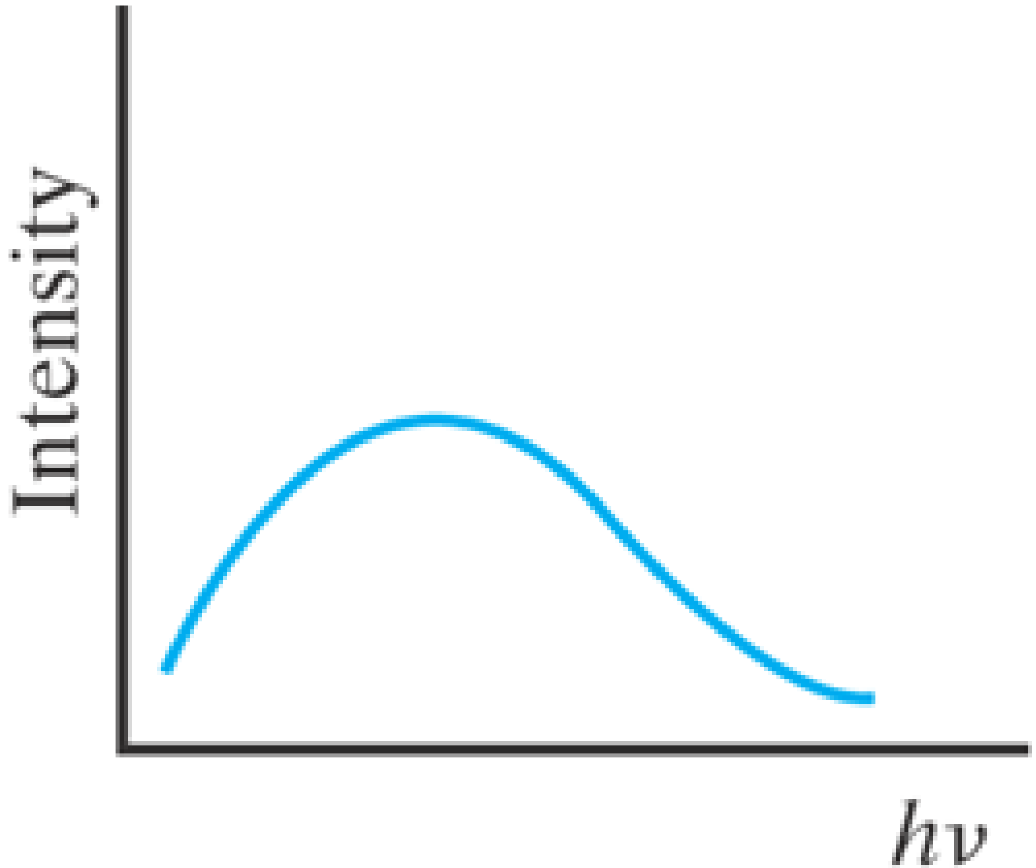
The process by which an incoming photon of specific frequency interacts with an excited electron, causing it to drop to a lower energy level (recombine) emitting a second phonon with the same:

- frequency
- phase
- direction
- polarization

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

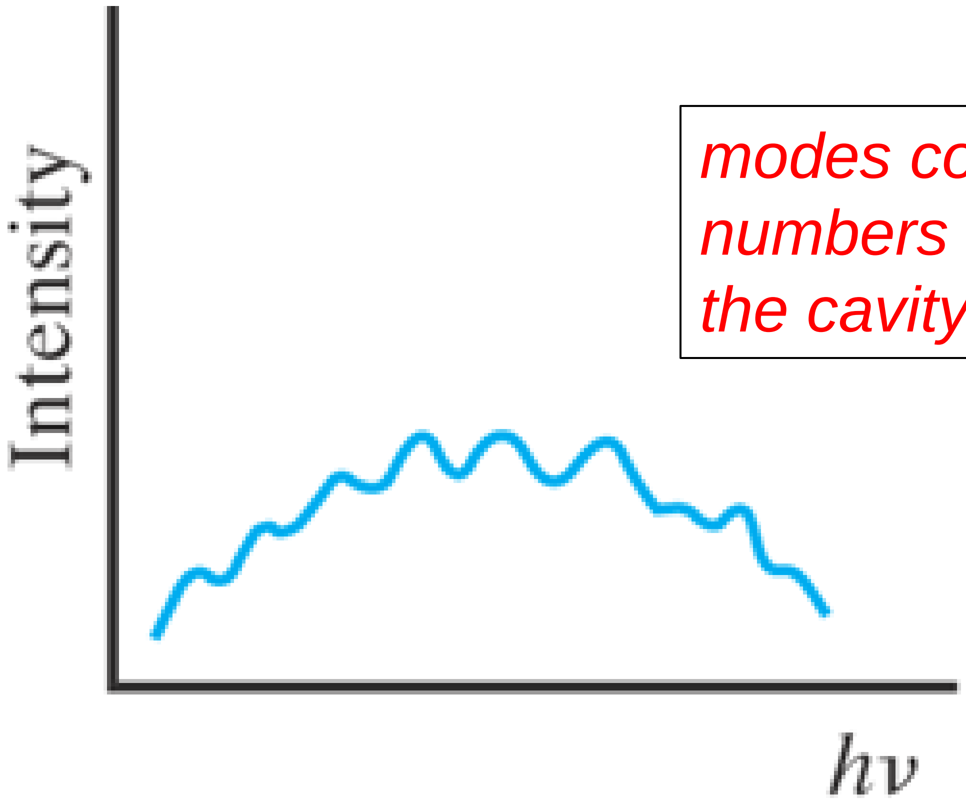
Below threshold

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



Approaching threshold

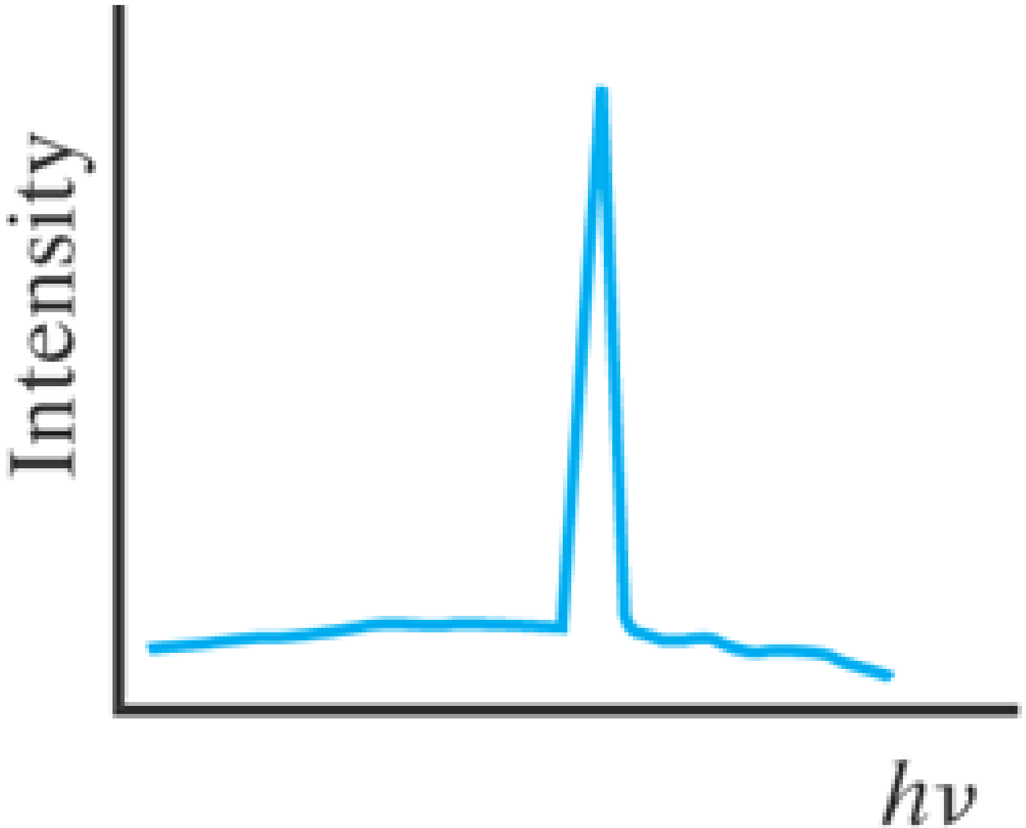
The photon wavelengths participating in the **stimulated emission** are determined by the length of the laser resonant cavity. As current increases, various cavity modes start to appear



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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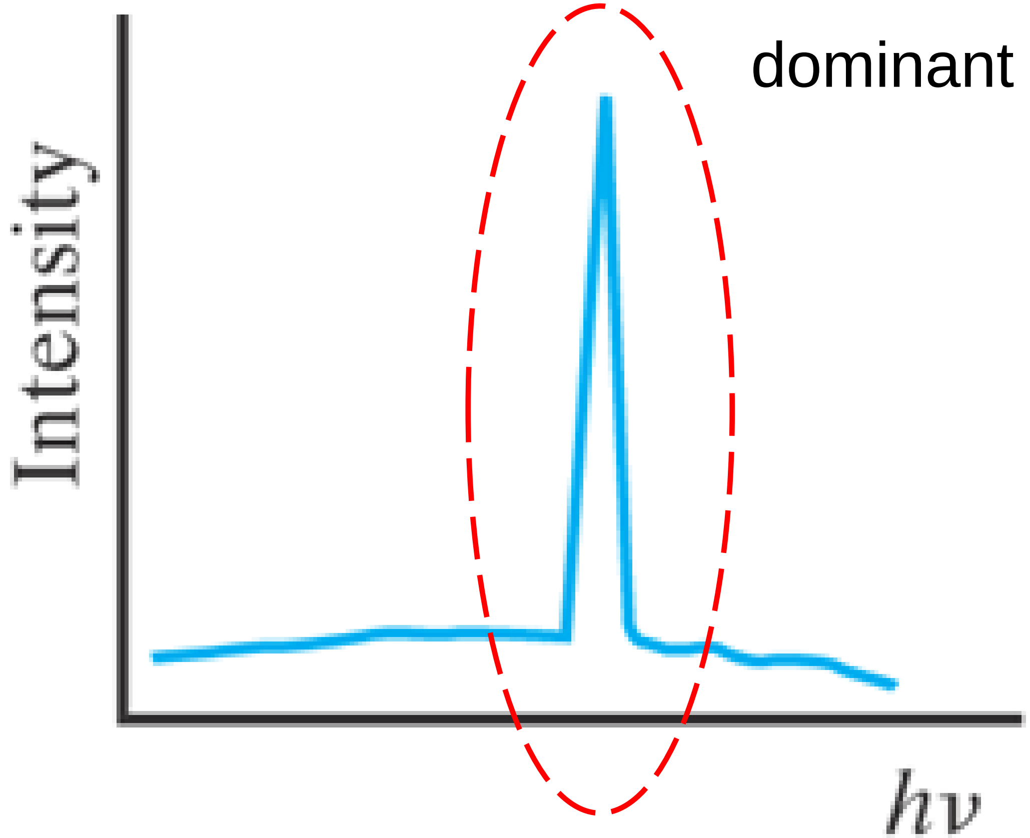

dominant nearly monochromatic radiation

The cavity structure favors stimulated emission

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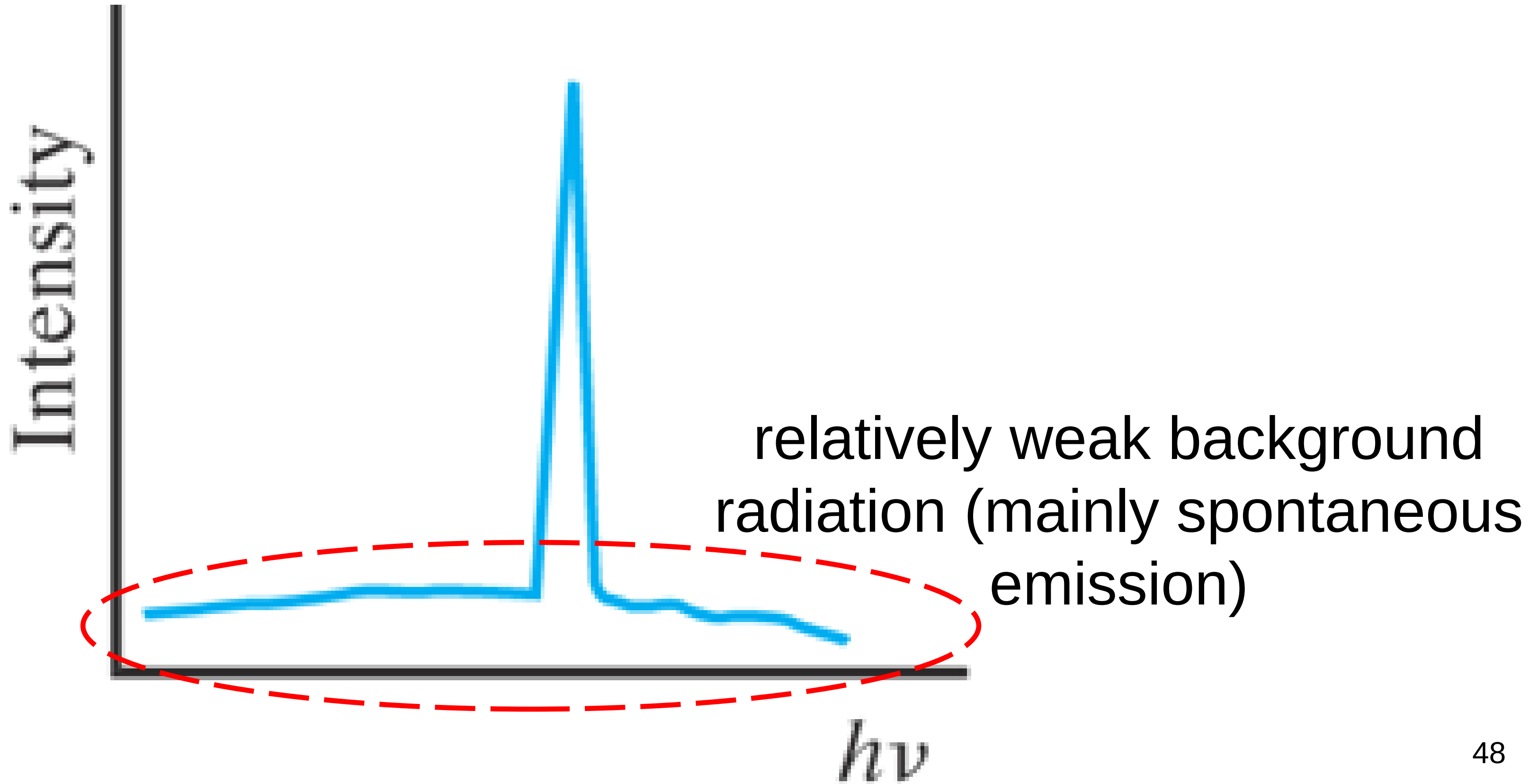
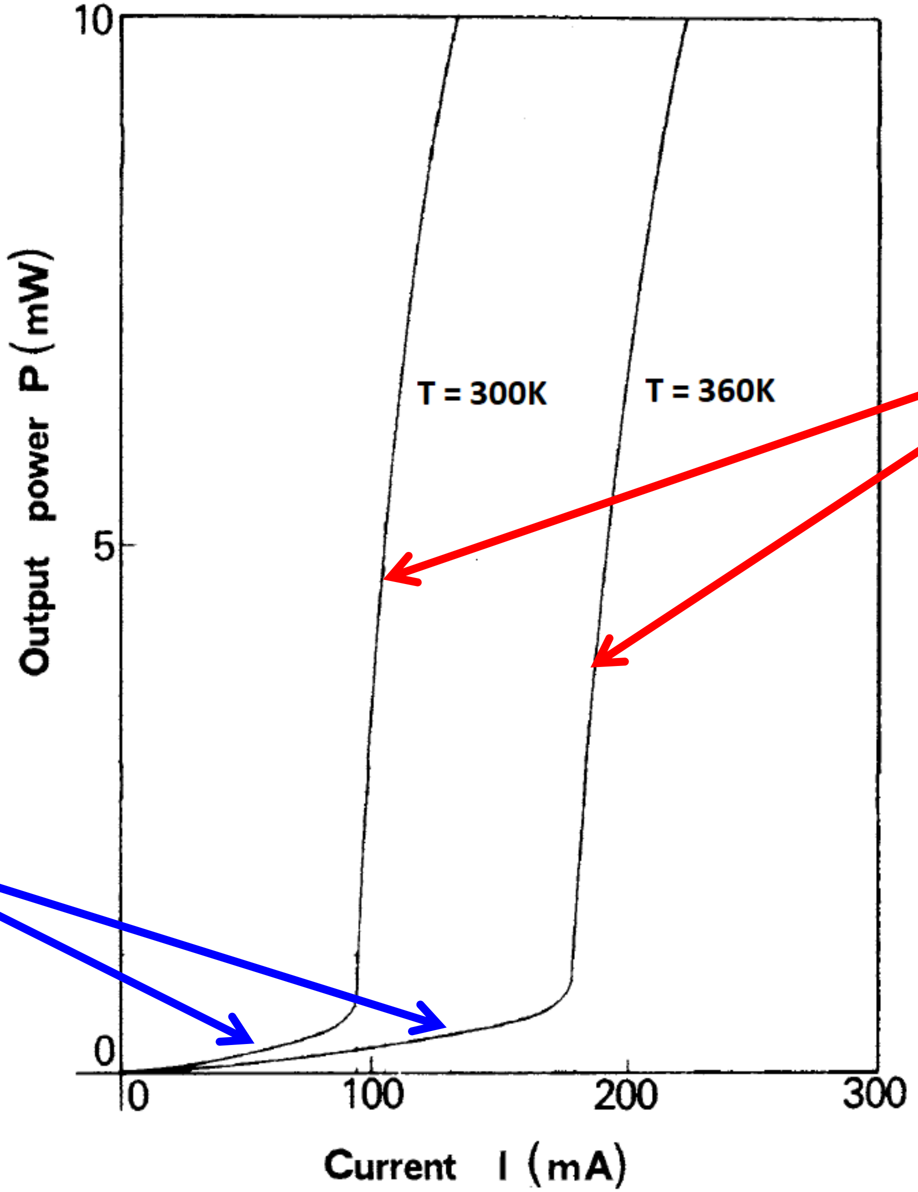


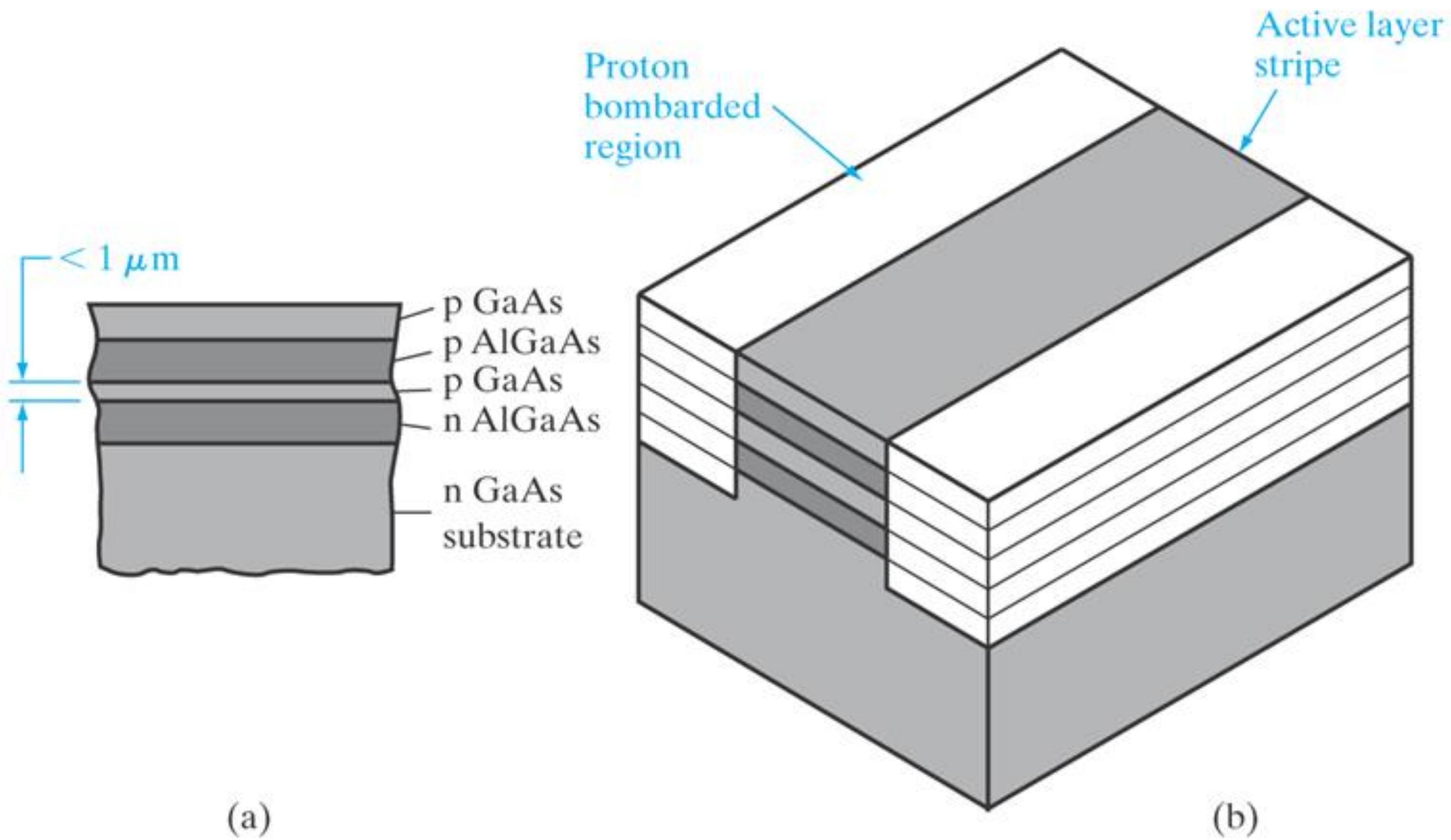
Laser – Power emission characteristics



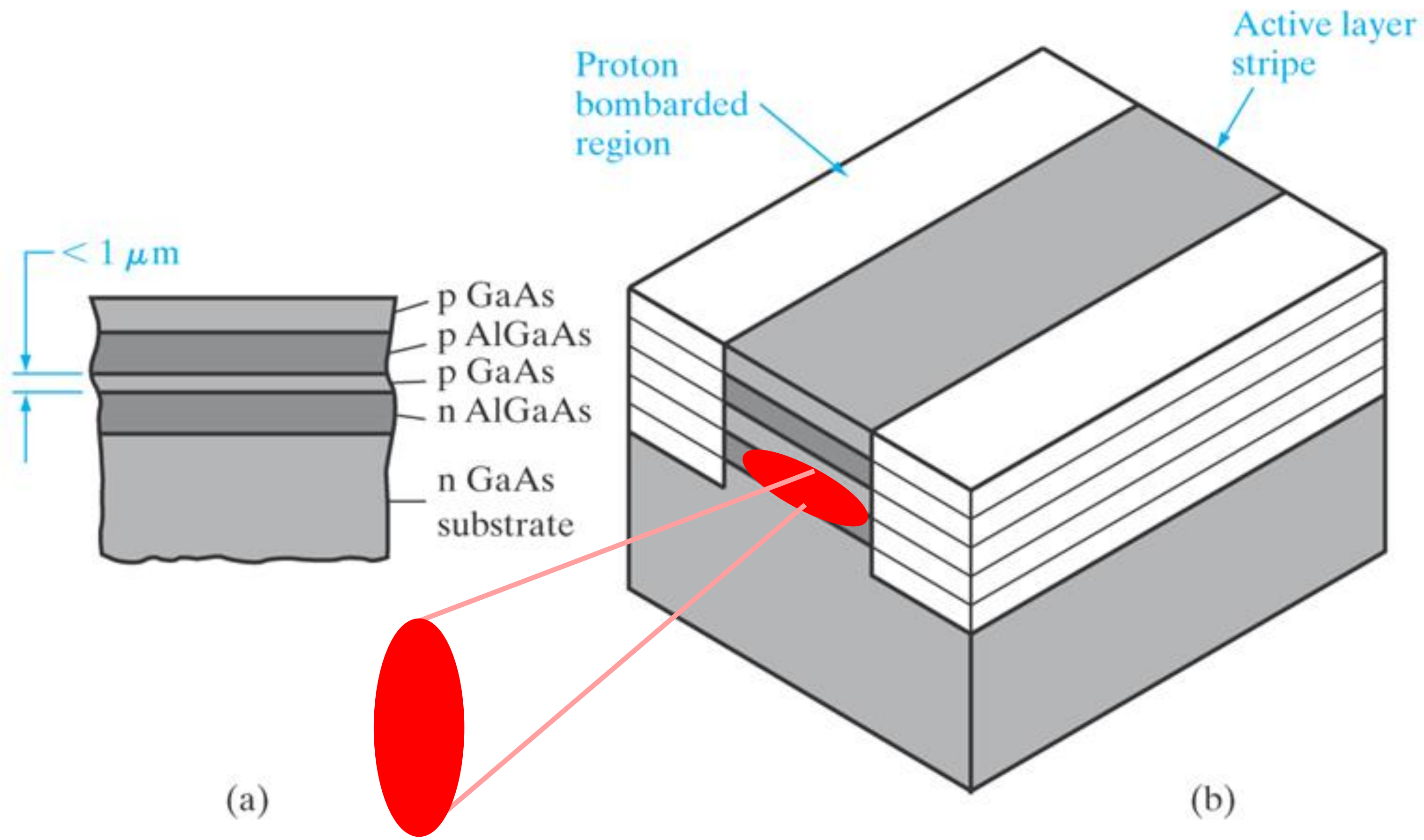
Above threshold stimulated emission dominates

Below threshold spontaneous emission dominates

Modern Double Heterojunction Laser



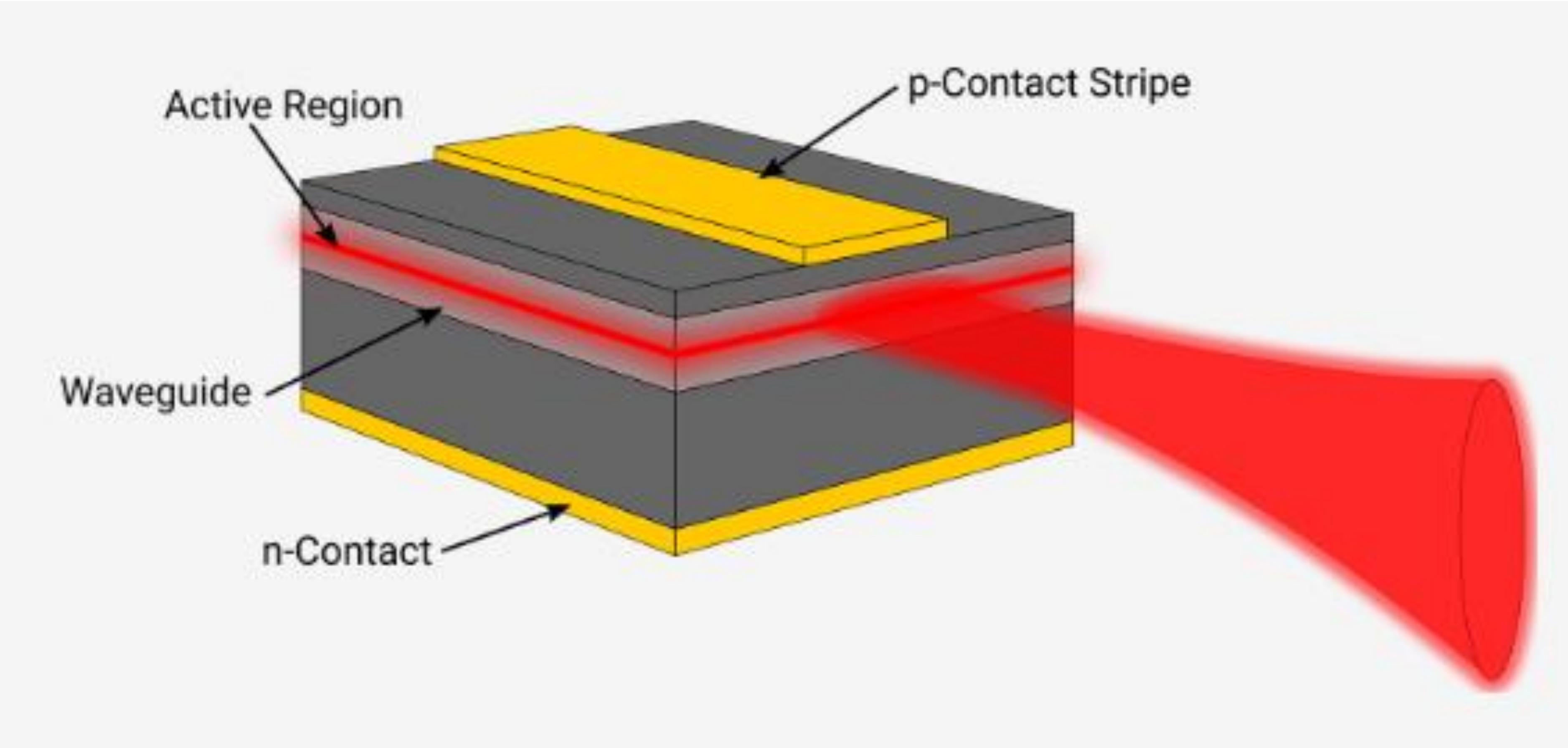
Modern Double Heterojunction Laser



EDGE EMITTING LASER

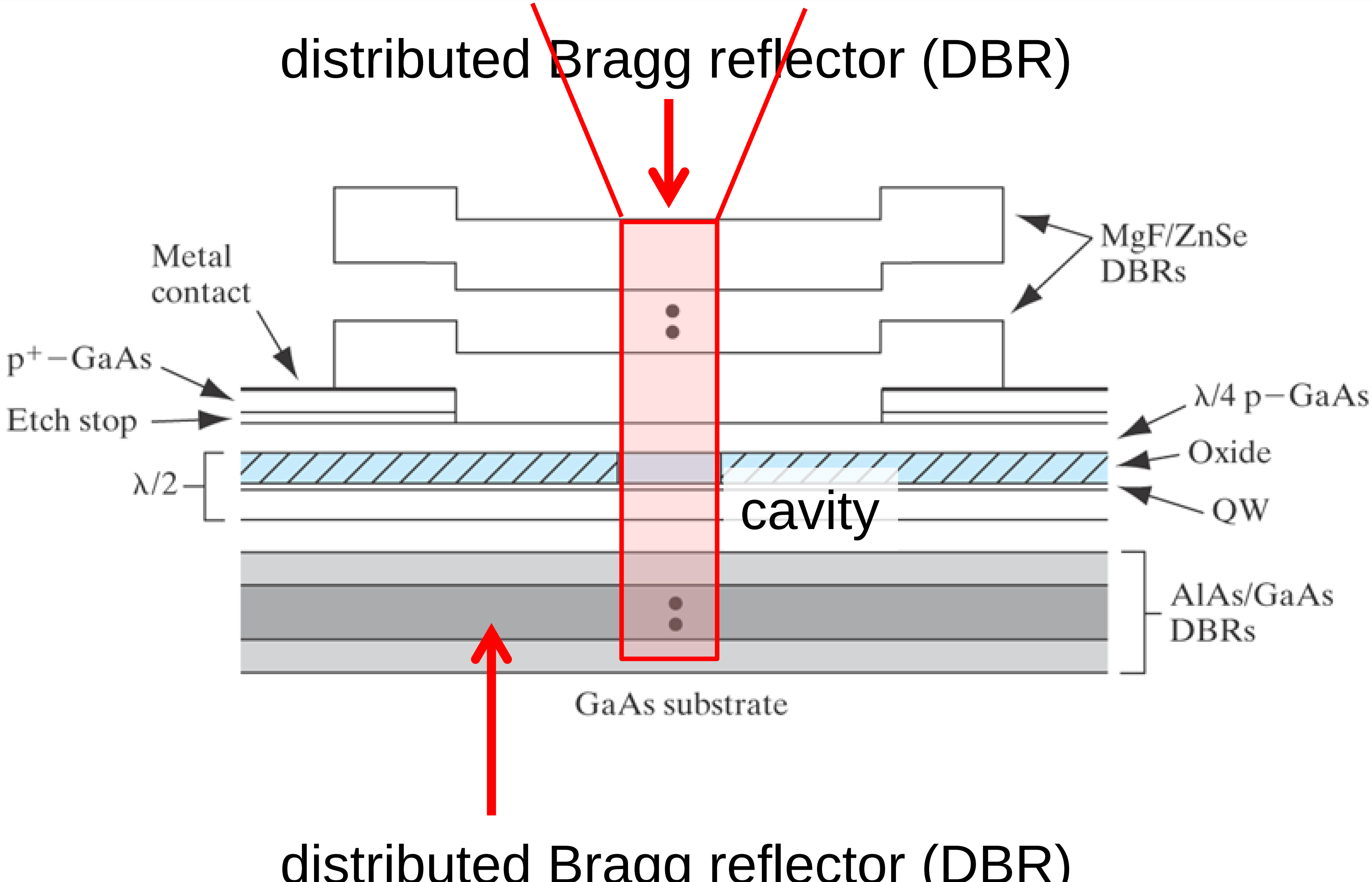
From *Solid State Electronic Devices,* Sixth Edition, by Ben G. Streetman and Sanjay Kumar Banerjee.
ISBN 0-13-149726-X.

Modern Double Heterojunction Laser

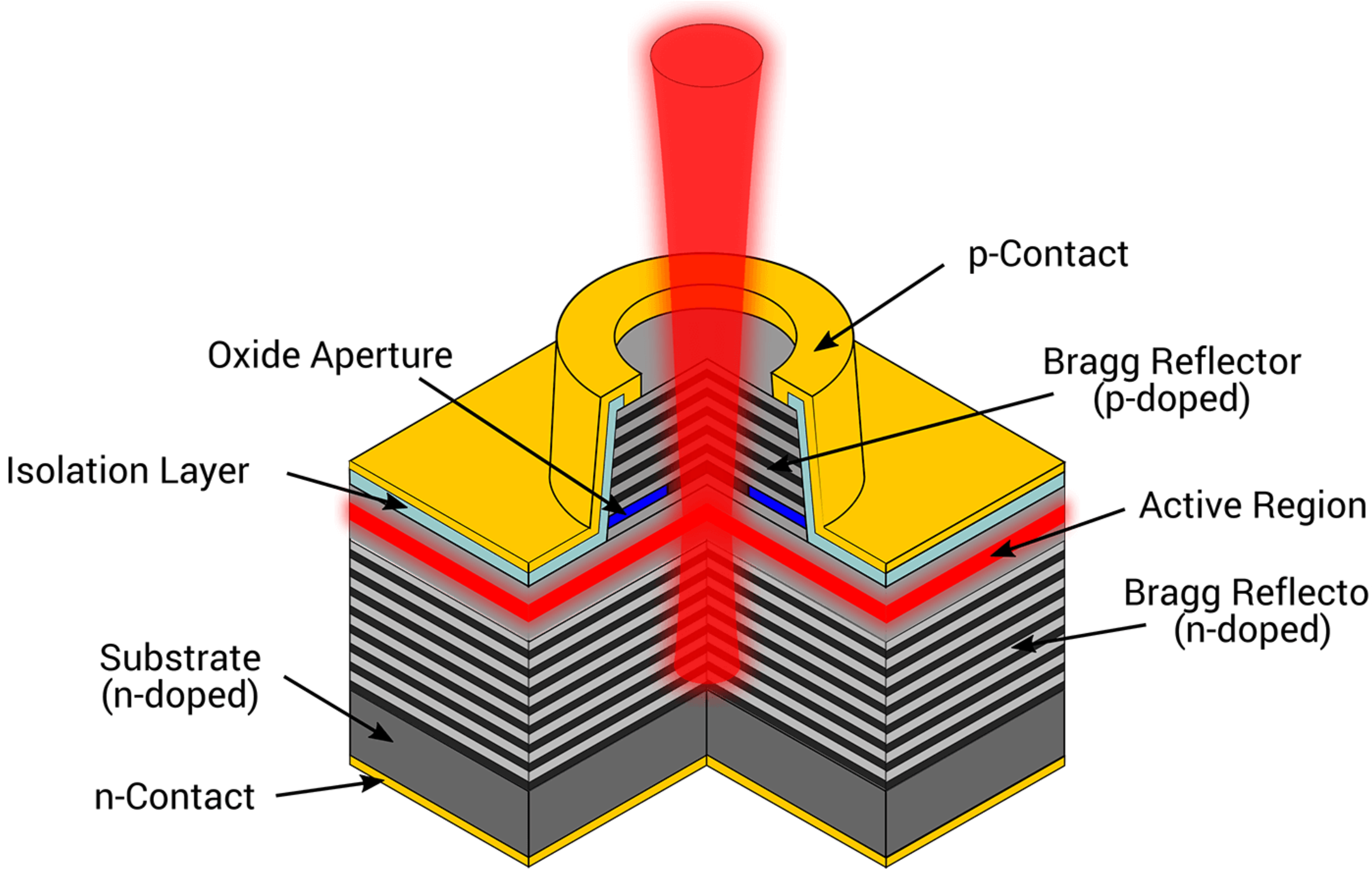


EDGE EMITTING LASER

Vertical Cavity Surface Emitting Laser (VCSEL)

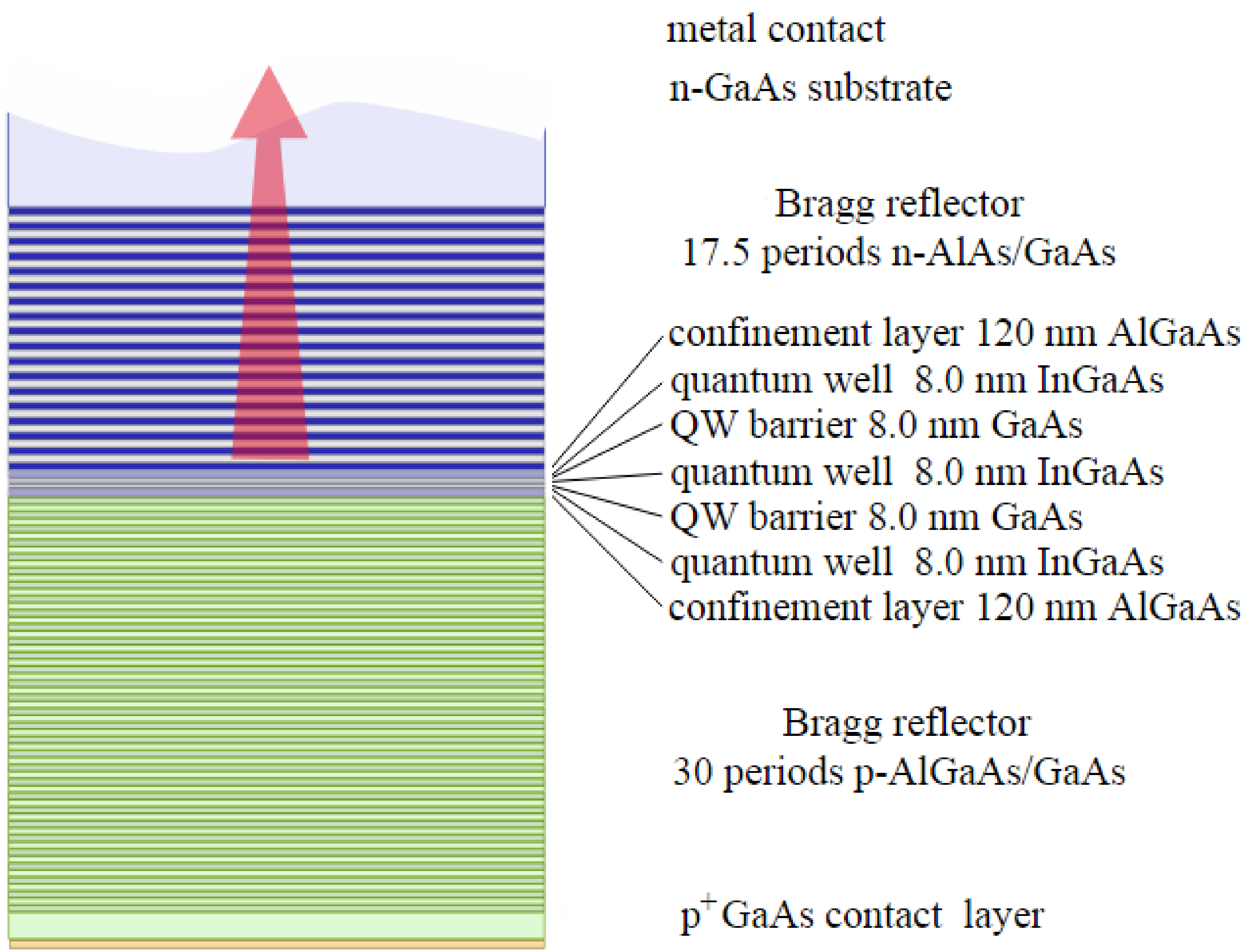


Vertical Cavity Surface Emitting Laser (VCSEL)

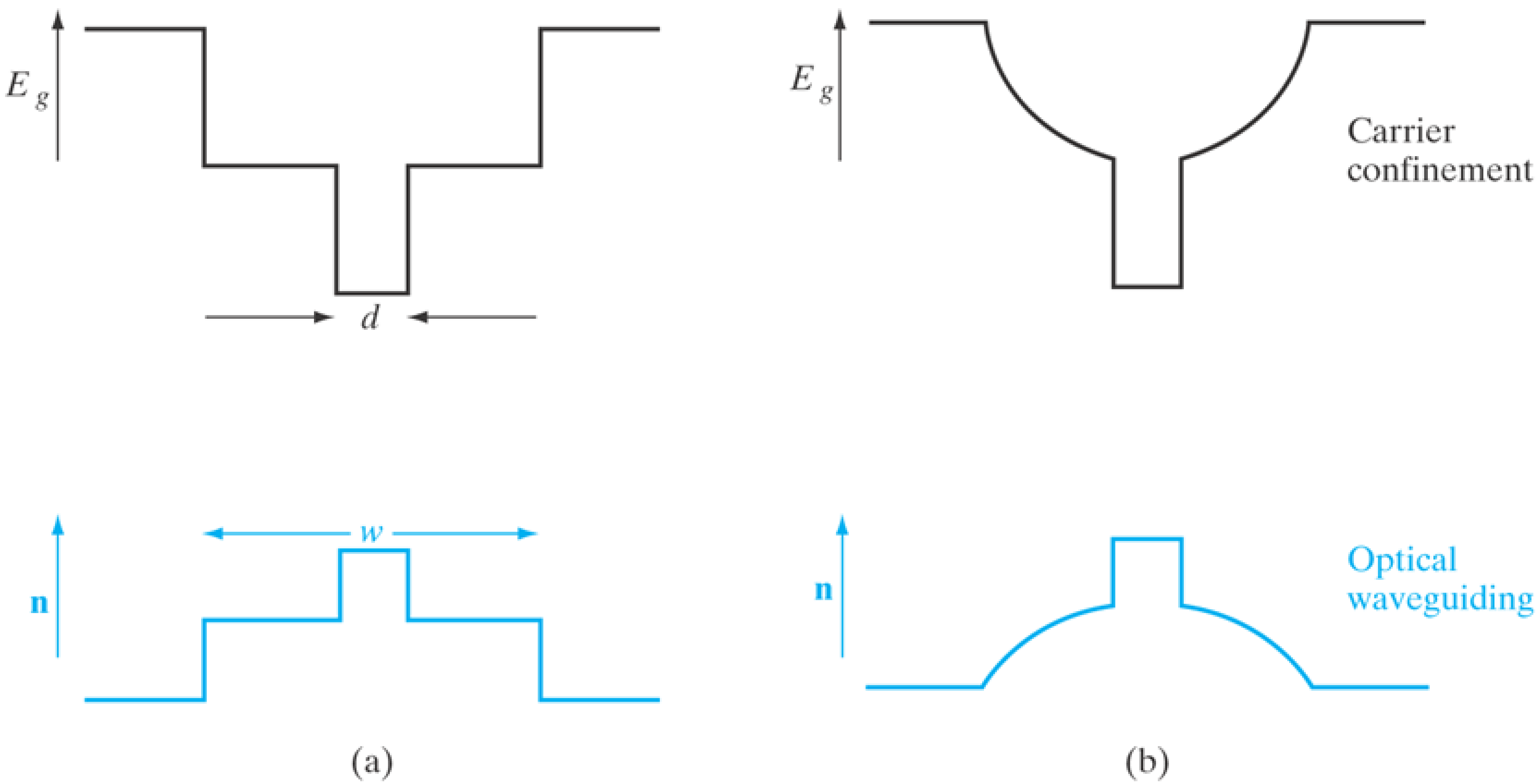


Reference: [Jetter, Roßbach, Michler (2013). Red Emitting VCSEL. In *VCSELs* (pp. 379-401). Springer Verlag]

Vertical Cavity Surface Emitting Laser (VCSEL)



Optical waveguiding and Carrier confinement



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