IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

Capteurs et Propagation

TAF OPE – PCPO et TAF STAR – CPC

Guided optical channel : physical interfaces

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LECTURE PLAN :

- Solid state physics refresher
  - Spontaneous and stimulated emission
  - PN junction
- Light Emitting Diodes
- Laser Diodes: Fabry-Perot and DFB
- Photodiodes : PIN and APD
- Detection noise: thermal, quantum, amplifier

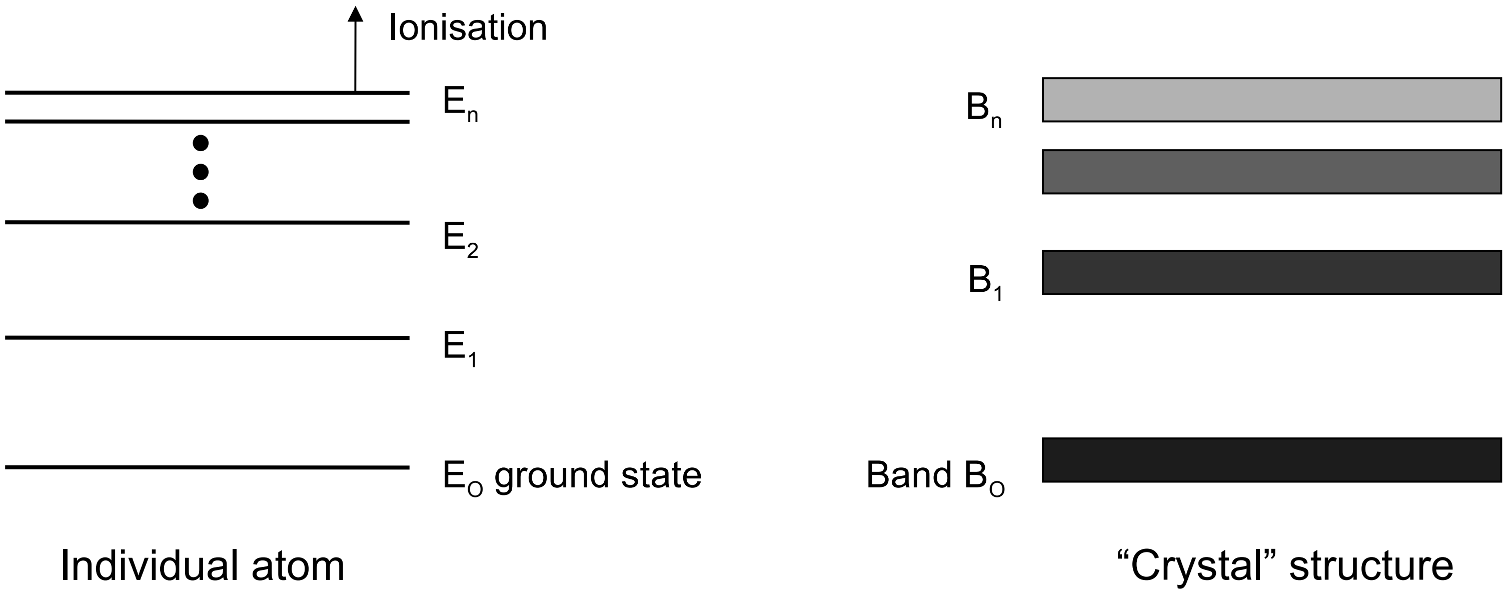
Solid state physics refresher (VERY simplified)

WHY ?

- **The light sources (transmitters) used in optical telecommunications are almost exclusively semiconductor based: LED, diode lasers.**
- **The detectors (receivers) used in optical telecommunications are almost exclusively semiconductor based: photodiodes.**
- **Many of the amplification techniques (EDFA, Raman, SOA) are based on solid state physics.**

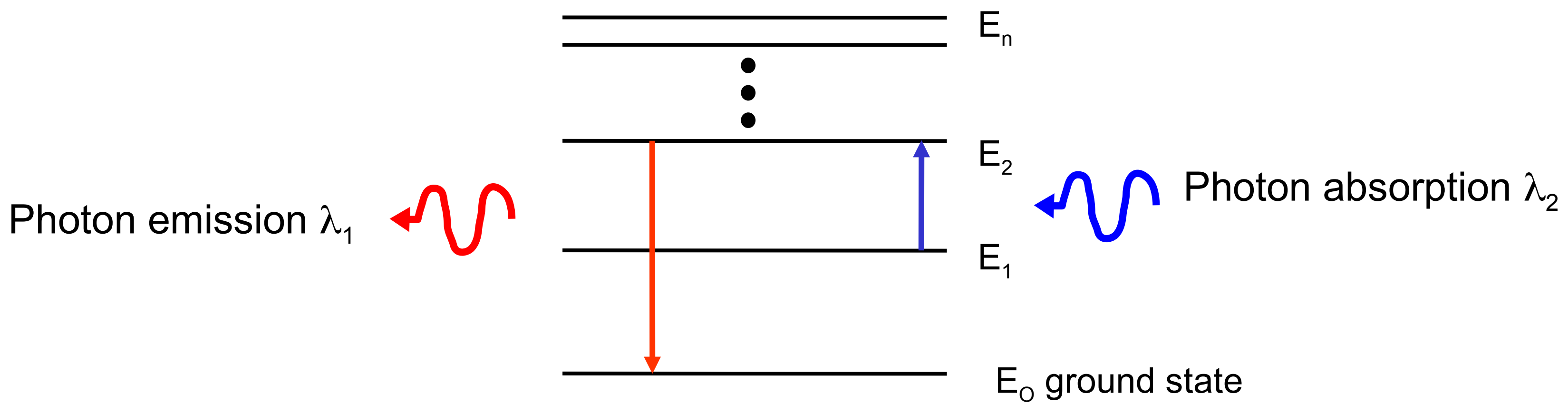
Energy levels and bands

- In individual atoms, electrons are bound to the nucleus but can occupy various **discrete energy levels** depending on their energy
- In solid structures (crystalline, semi-crystalline …) the energy levels become **energy bands** due to interactions between electrons and between crystal atoms via vibrations of the crystal lattice (“phonons”)



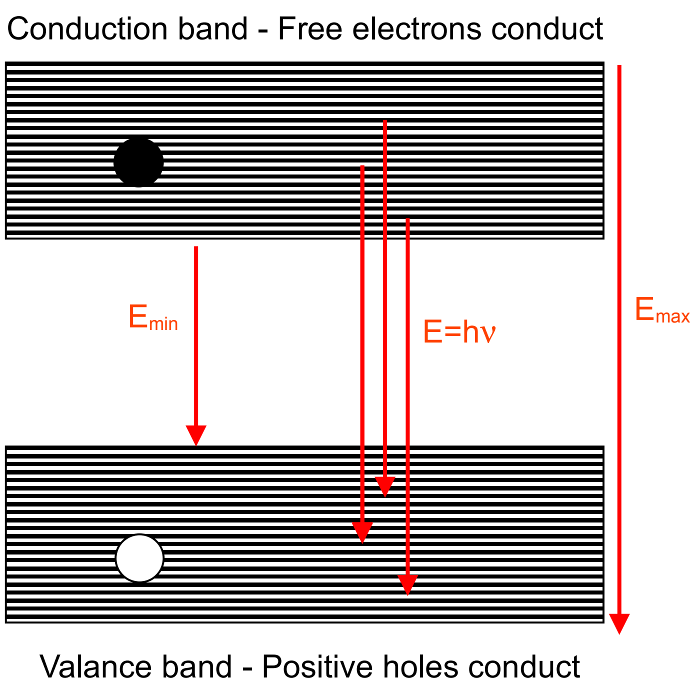
Photons and energy levels

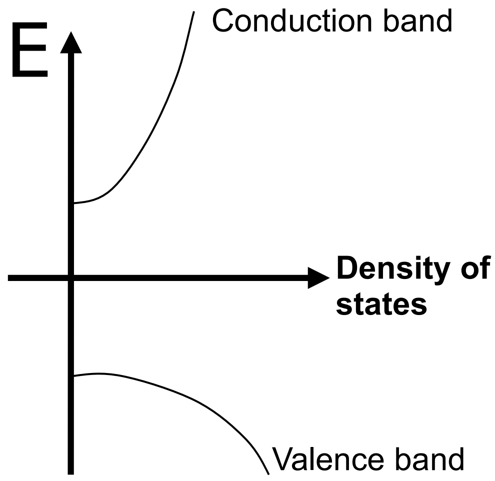
- When an excited (thermal, electrical …) electron drops from a higher energy level to a lower one it emits the energy difference as an electromagnetic wave : a photon of a specific wavelength/frequency ($E=h\nu$).
- A lower energy state electron can also absorb a photon, causing the electron to be excited to a higher energy state (again energy difference $E=h\nu$)
- The separation between energy levels and bands depends on the different types of atoms and the crystal structure : different materials absorb/emit light of different wavelengths

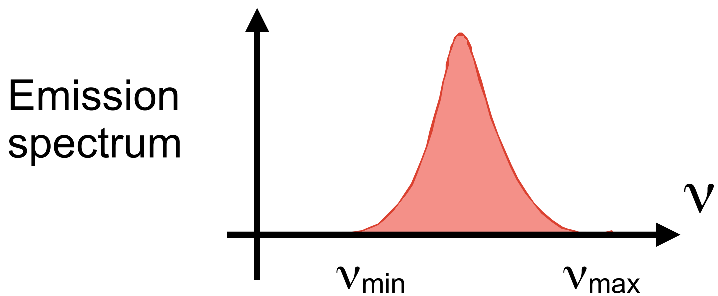


Energy bands - emission/absorption spectrum

- The discrete levels of atoms lead to quasi-monochromatic emission/absorption
- The energy bands of crystals lead to wider emission/absorption spectra because many transitions of slightly different energy are possible … with differing probabilities

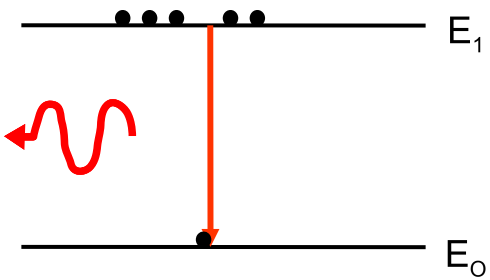




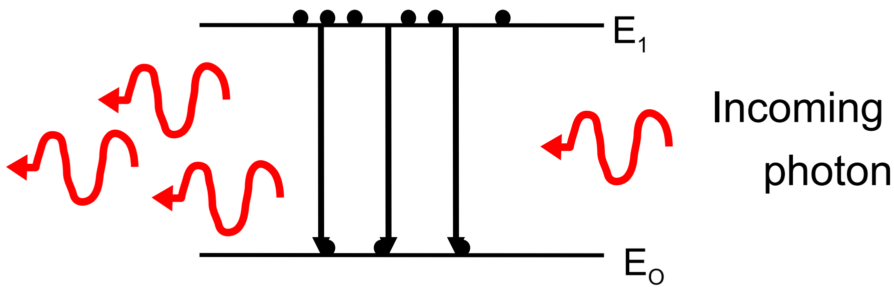


Spontaneous and stimulated emission

- A light source emits photons when excited electrons fall to lower state : usually occurs at random times with a given probability = **SPONTANEOUS** emission.
- The presence of another photon of the correct wavelength (energy) increases the probability of emission : **STIMULATED** emission.
- **Spontaneously** emitted photons are **incoherent**, have **isotropic directions** and can have **different wavelengths** limited by the electroluminescence band.
- **Stimulated** photons have the same **phase, wavelength, polarisation** and **direction** as the stimulating photon = coherent.



Spontaneous emission

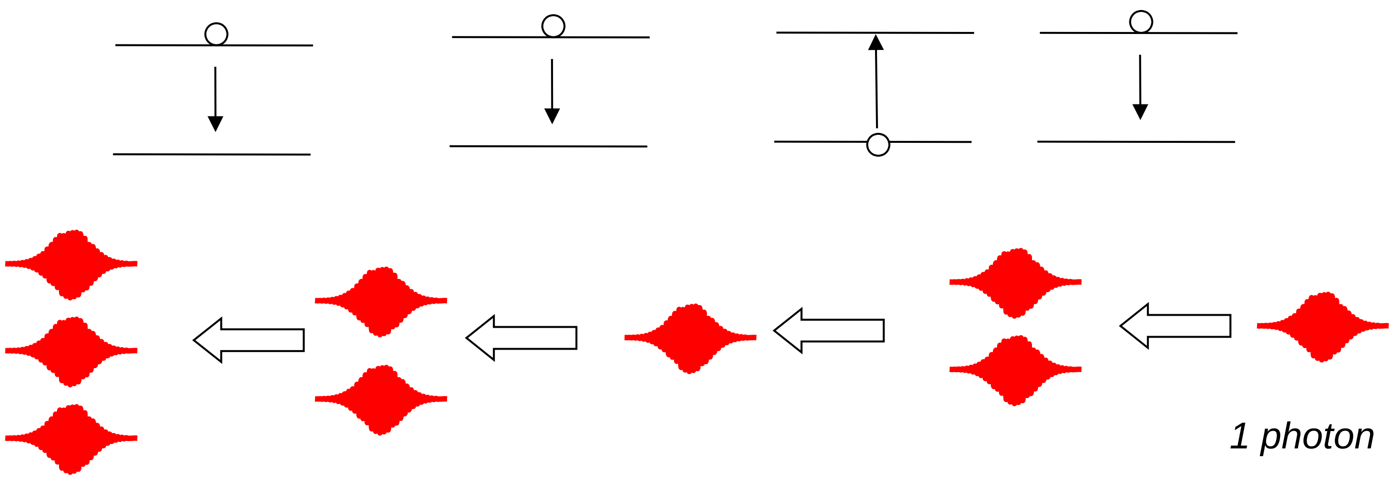


Stimulated emission

Photon energy : $E = h\omega = E_1 - E_2$

Amplification principle

One incoming photon generates several (coherent) photons by stimulated emission



Stimulated emission must be more likely than absorption

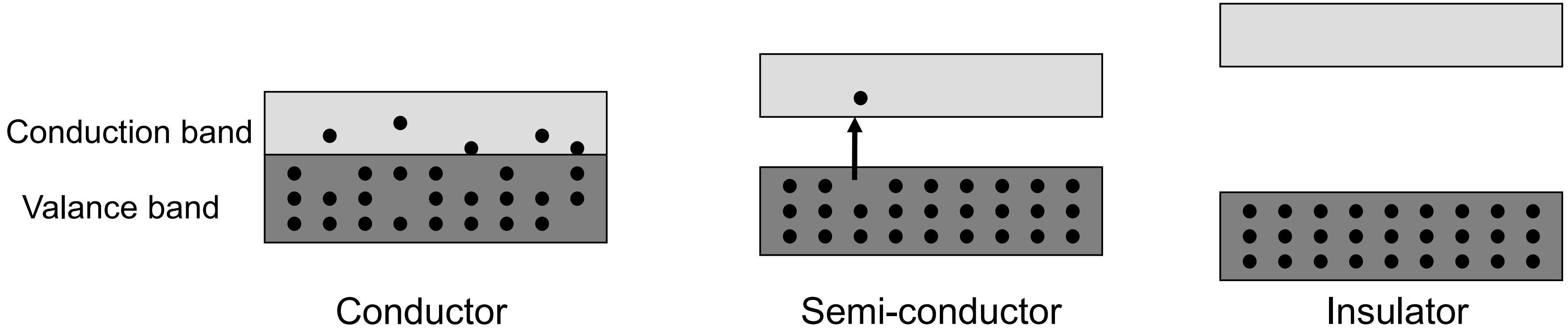
P_a = Probability of absorption of a photon per unit time.

P_e = Probability of stimulated emission of a photon per unit time

Gain: $G \propto (P_e - P_a)$

Band occupation in crystal type structures

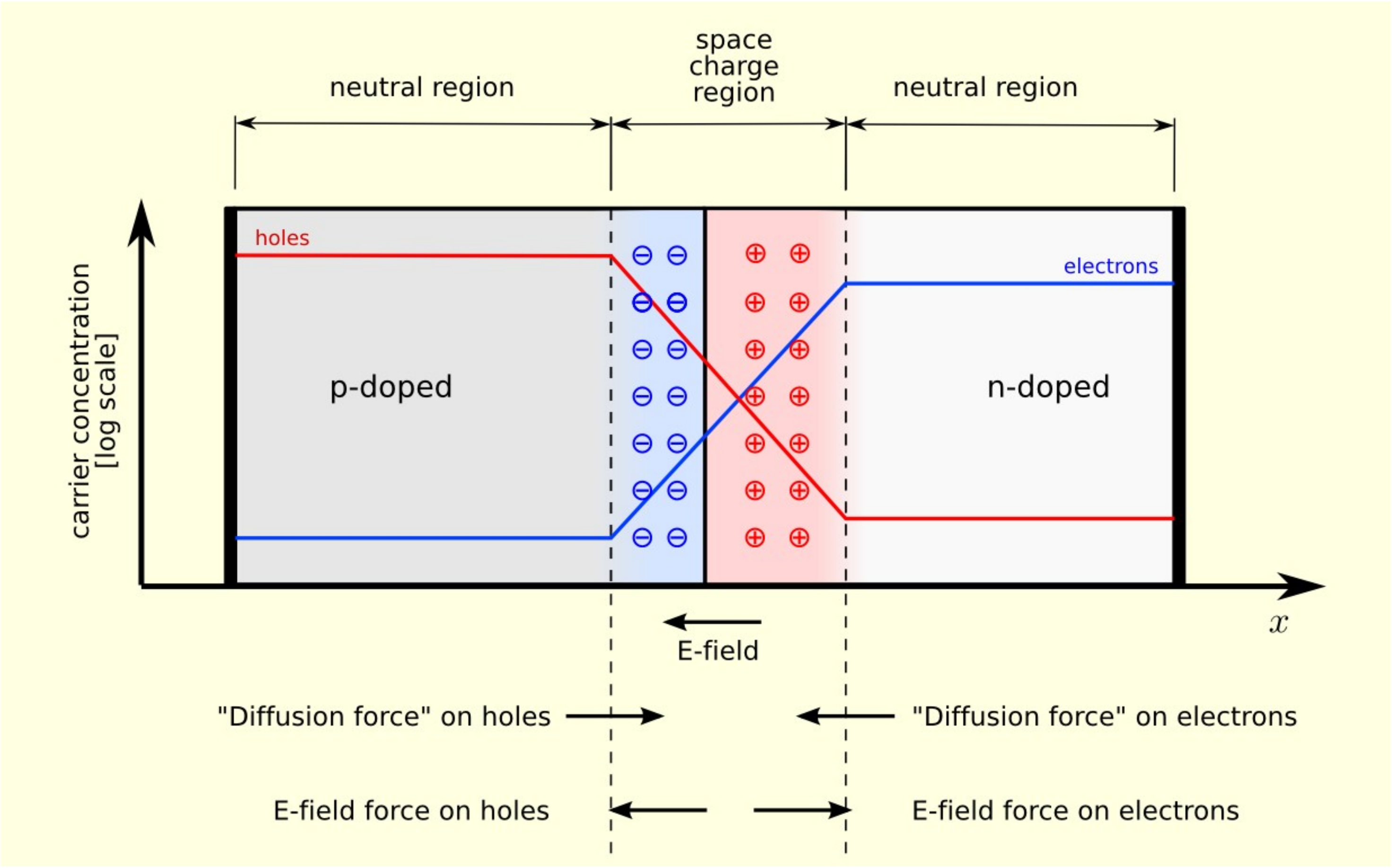
- The occupation of the energy bands by the electrons depends on the number of available electrons and the number, width and separation of the bands.
- In **electrical conductors** (e.g. metals) the top band (“valance” band) is not completely full. Electrons can easily find close, free levels or “states” within the band which enable them to move and conduct electricity.
- In **insulators**, the lower band (valance) is full and the gap to the next band (conduction) is too large for the electrons to be thermally excited to it. Electrons therefore cannot reach free energy levels and cannot conduct electricity.
- In **semiconductors**, the valance band is full but the separation or “band-gap” to the conduction band is small so a proportion of electrons can reach it by thermal excitation at room temperature and so conduct electricity.



P-N junction (greatly simplified !)

- A semiconductor crystal can be **“doped”** by inserting small quantities of other atoms that are electron donors (N-type) or receptors (P-type)
- An N-doped semiconductor will have an excess of electrons which can then become mobile in the crystal
- A P-doped semiconductor will have positive “holes” (missing electrons) which can also become mobile by electron transfer
- Opposite doping of adjacent areas of a semiconductor crystal : **PN junction**.
- The excess electrons and holes diffuse across the junction creating a charge imbalance and hence an electrical field which stops further charge flow and creates the “space-charge region” or “**depletion layer**” around the PN interface
- If the PN junction is **“forward biased”** (P-doped section connected to a electrically positive terminal and N-doped to a negative terminal), charge flow will decrease the depletion layer and the junction will conduct electricity
- If the PN junction is **“reverse biased”** charge flow will increase the depletion layer size and electrical field and the junction will not conduct.
- The PN junction functions as a **diode** – electrical current in one direction only.

P-N junction schematic



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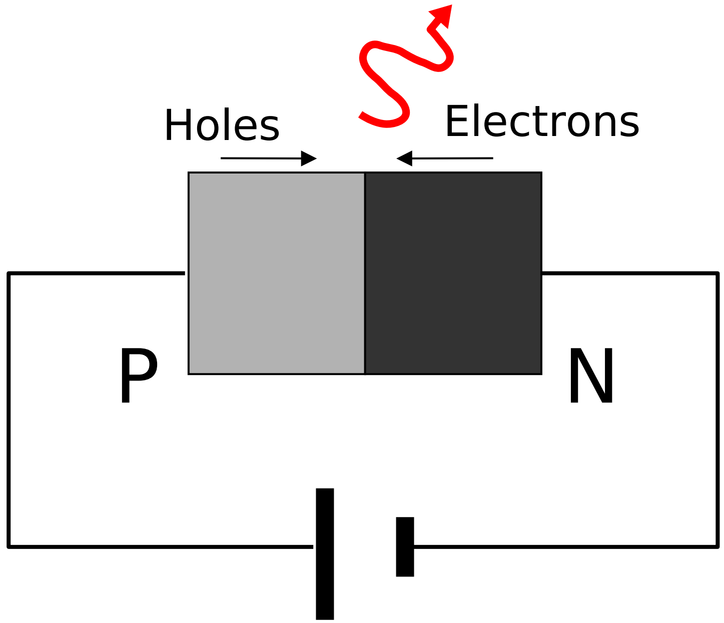
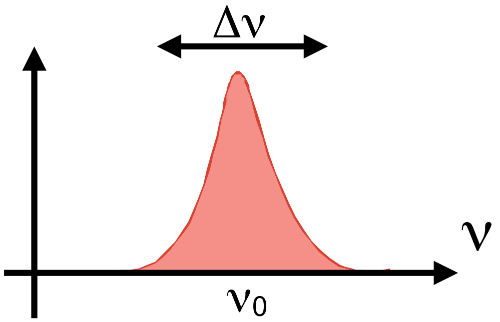
Light Emitting Diodes (LED)

- PN junction in a suitable semiconductor material (chosen for the bandgap value).
- When the correct voltage is applied (forward-bias) current flows forcing electrons (in the conduction band) and holes (in the valance band) into the junction area.
- Electron-hole recombination occurs in the junction area (an electron falls from the higher energy conduction band to the lower energy valance band), accompanied by the emission of a photon to release the excess energy
- Electrical energy is converted to light energy.
- Emitted light spectrum determined by semiconductor band structure and bandgap





Emission spectrum

Light Emitting Diodes

- Spontaneous emission → Incoherent, non-directive (surface or edge) emission of light.
- Wavelength depends on material bandgap, e.g. GaAs ~ 1eV for photons in the visible-IR
- Spectral width depends on the widths of the energy bands and temperature ($\Delta\nu$ ~ 1.5 kT/h). Typical values from 10-100nm.
- LEDs based on different materials and compounds available from the UV to IR
- Advantages for telecommunication
  - Simple, compact, reliable, efficient, very low cost devices
  - Can be directly modulated (vary drive current)
- Disadvantages for telecommunications
  - Spectrally wide (~10-100nm), severe dispersion, WDM difficult
  - Non-directive emission difficult to couple into fibres.

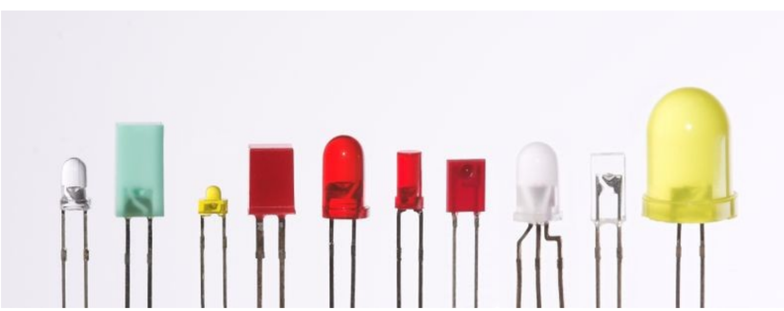
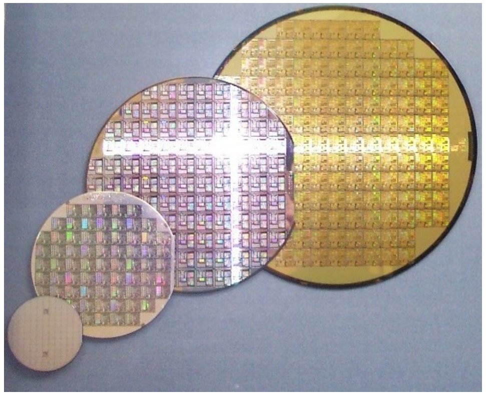
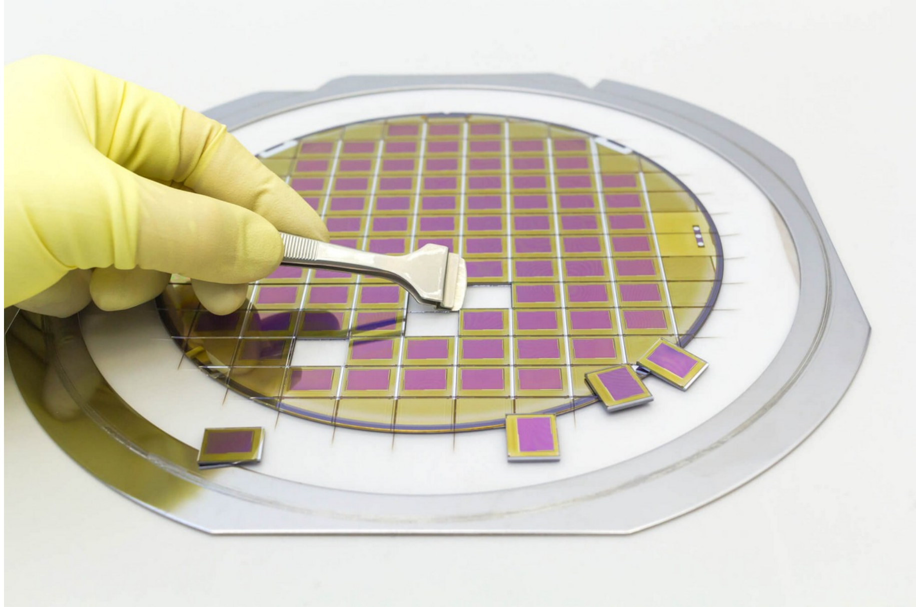


Image www.wikipedia.org

“Wafer” production of semiconductor LED/lasers

- Semiconductor LED/lasers are fabricated (mass production) on a wafer – the same process as micro-electronic “chips” : processors, memory ...
- A wafer is patterned (photolithography) and locally doped (P or N) to produce the required PN junctions at desired locations
- The wafers are then “diced” (cut up) or “cleaved” into separate components
- Wafer sizes range from 1’ (25mm) to 12’ (300mm) so 10^3 to 10^5 devices per wafer (depending on device size) can result in very low costs per device.





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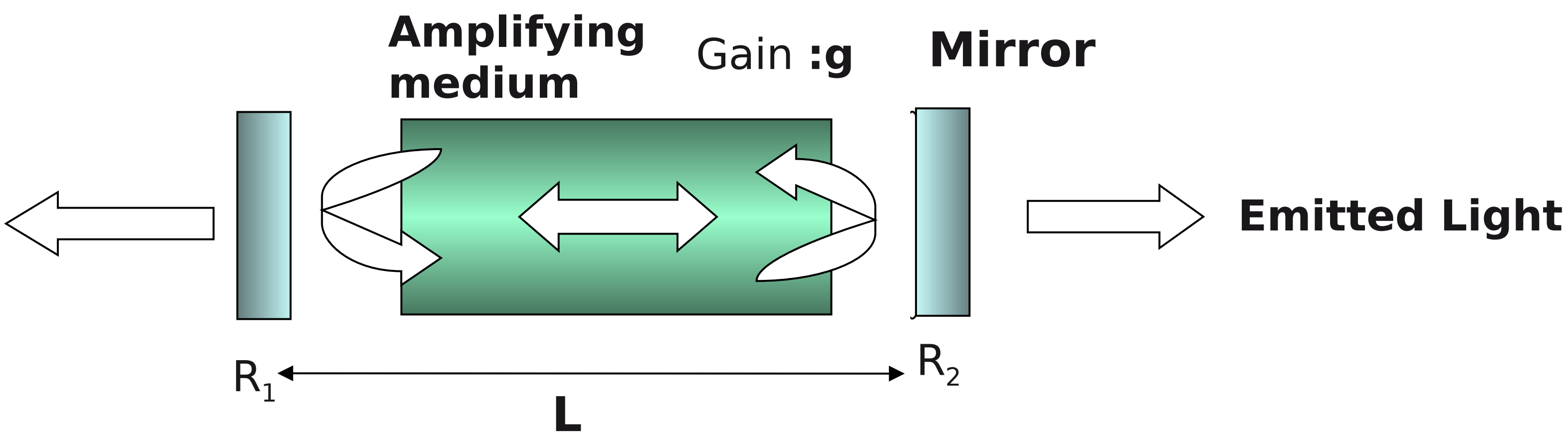
"A LED in a resonant cavity"

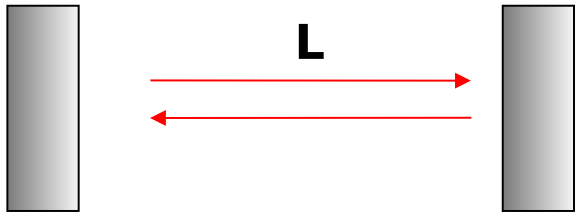
- The semiconductor material acts as an optical amplification medium – amplification based on **stimulated emission** process

- The resonant cavity (Fabry-Perot) reduces the **spectral width**, improves the **output power** (gain) and increases the **directivity**



Fabry-Perot Cavity

- A Fabry-Perot cavity, made up of two (“parallel”) mirrors, only “resonates” for certain wavelengths

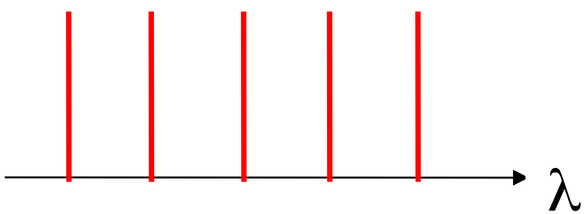


- The optical length of the cavity (L) must be a multiple of the resonant wavelength to form standing waves

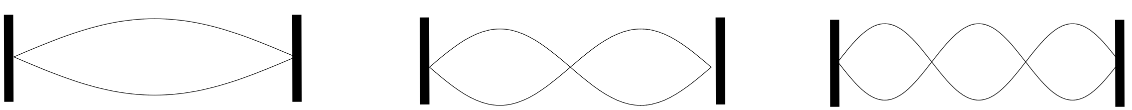
$$n\frac{2\pi}{\lambda}2L = 2k\pi \Rightarrow \lambda_k = \frac{2nL}{k}$$

- The resonant spectrum of Fabry-Perot cavity therefore consists of a series of equally spaced narrow lines.

$$\Delta\lambda_m = \frac{\lambda_0^2}{2nL}$$

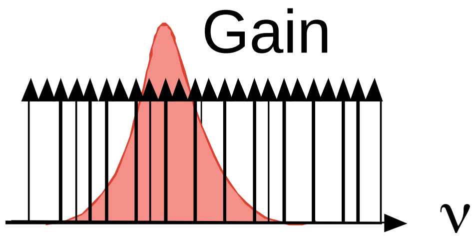


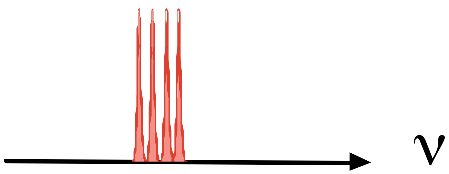
EM fields in the cavity:



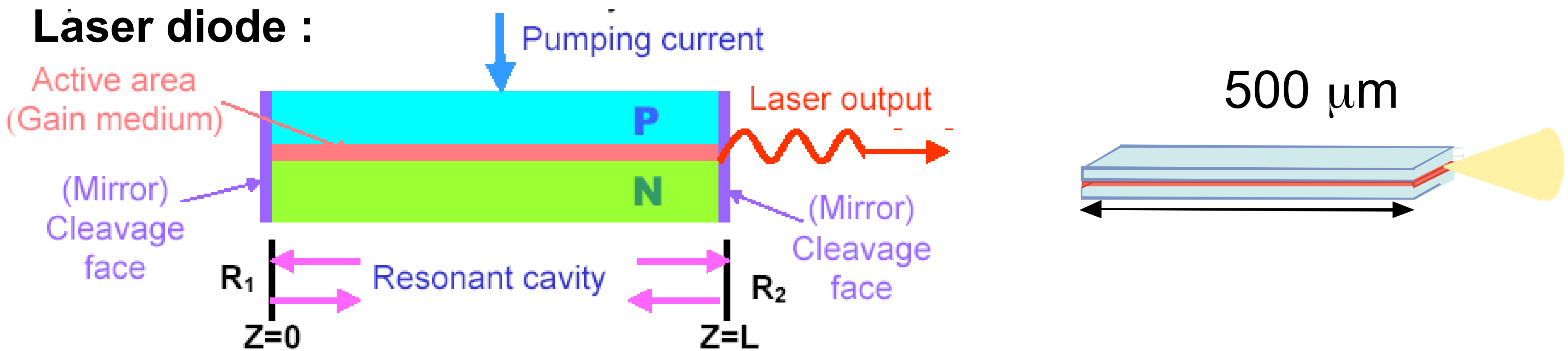
Semiconductor laser

- The Fabry-Perot selects a limited number of wavelengths from the emission spectrum of the semiconductor material, greatly reducing the overall spectral width compared to a LED
- Repeated passages across the cavity produce more stimulated emission and gain, improving output power, directivity and coherence
- Typical laser diode structure – thin slab of cleaved semiconductor material, cleaved faces act as mirrors.





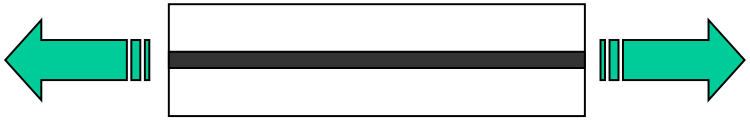
Laser diode :



Different types of semiconductor laser.

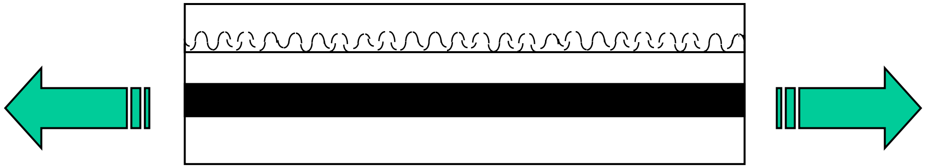
- **To further reduce the laser spectral width (lower dispersion) :** a wavelength selective structure – typically a Bragg grating – is added somewhere in the laser cavity to select only one of the Fabry-Perot modes.

Fabry-Pérot laser :



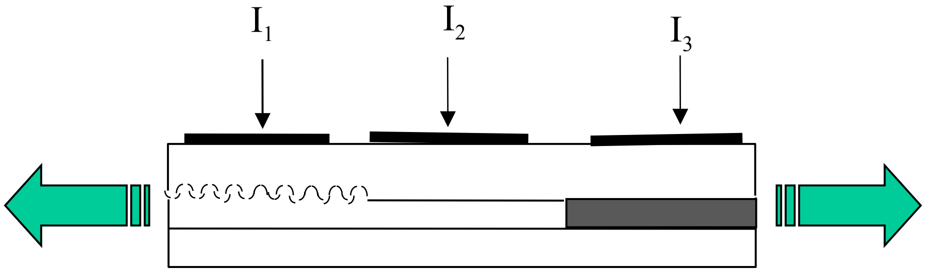
DFB laser:

Distributed Feedback



DBR laser :

Distributed Bragg Reflector:

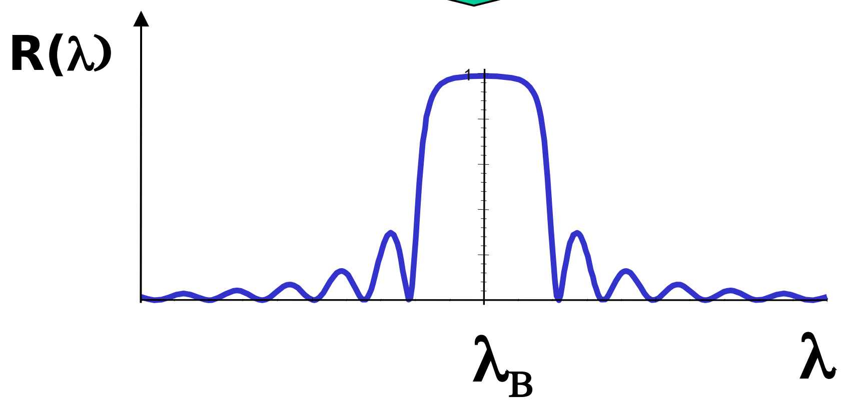


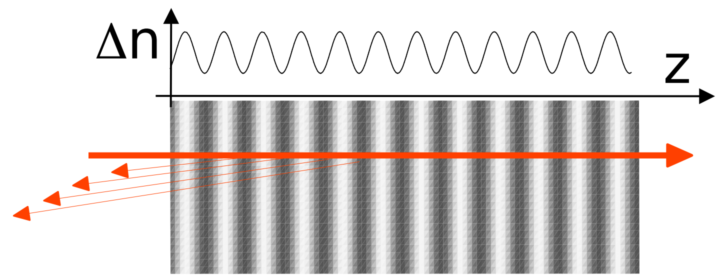
Bragg Mirror

- **Bragg Mirror =** periodically varying refractive index (etched, photo-inscribed).
- Waves reflected at interfaces interfere constructively for one wavelength only
- Highly wavelength selective mirror

Condition for Bragg reflection :

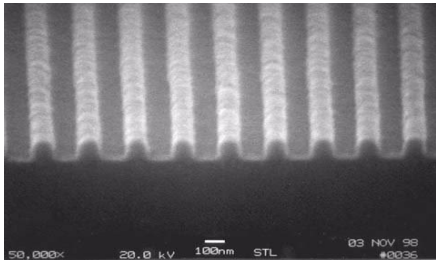
$$\lambda_B = 2n_0\Lambda$$





Index grating period : Λ

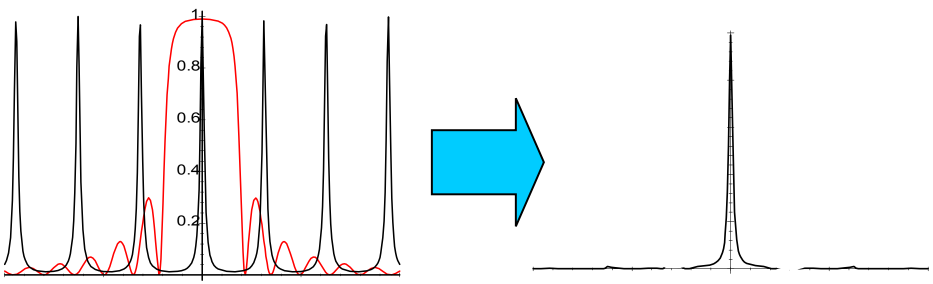
Average grating index : n_0



DBR lasers

Bragg filter:

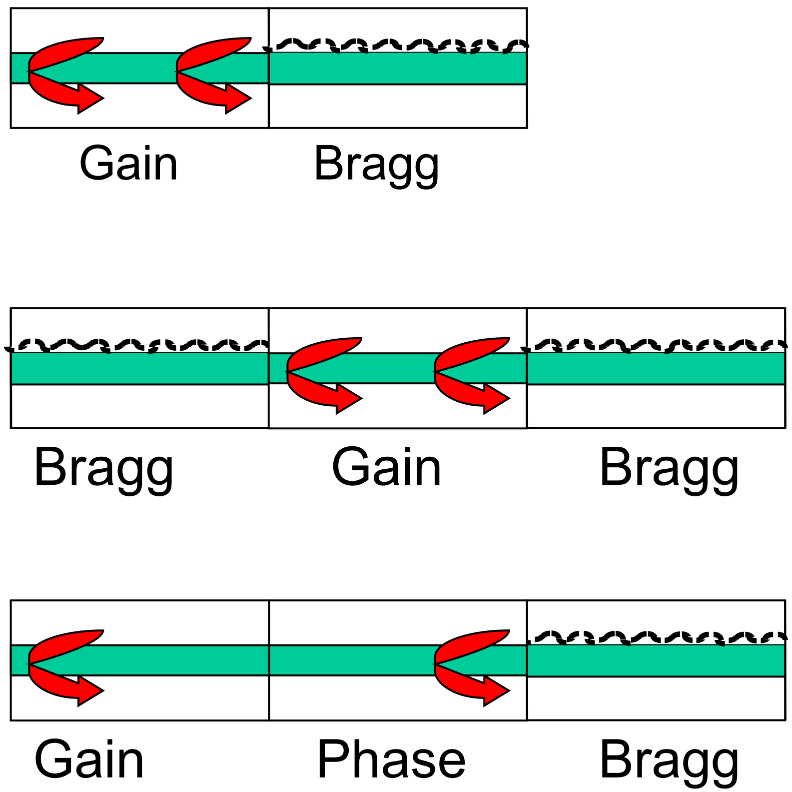
Filtering of FP modes ⇒ Singlemode operation



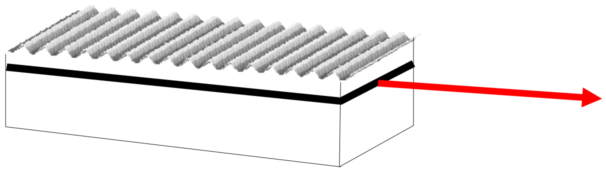
Tuneable wavelength possible by varying drive current to the different sections

Tuning range	10 nm
Optical output power	10 - 100 mW
Spectral width	10^{-2}, 10^{-3} Å
Threshold current	10 mA

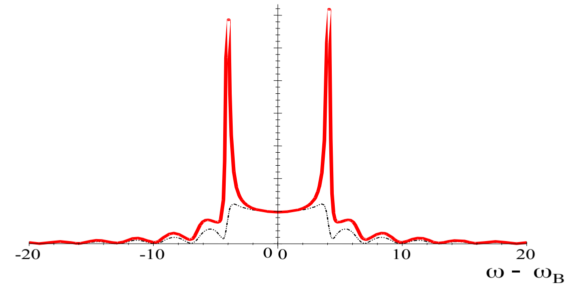
DBR structures :



DFB Laser

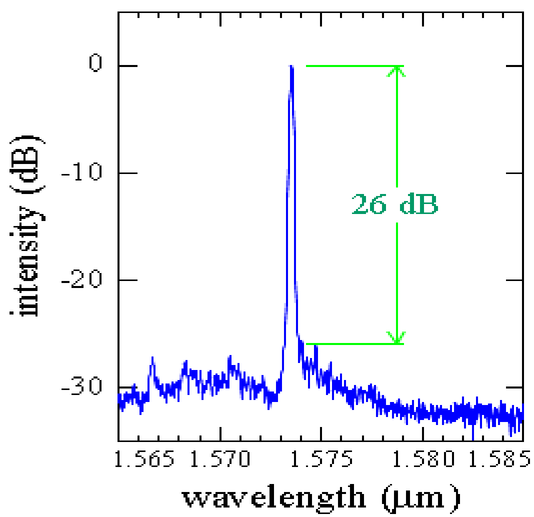


DFB laser structure



DFB laser emission spectrum

Phase step in grating structure

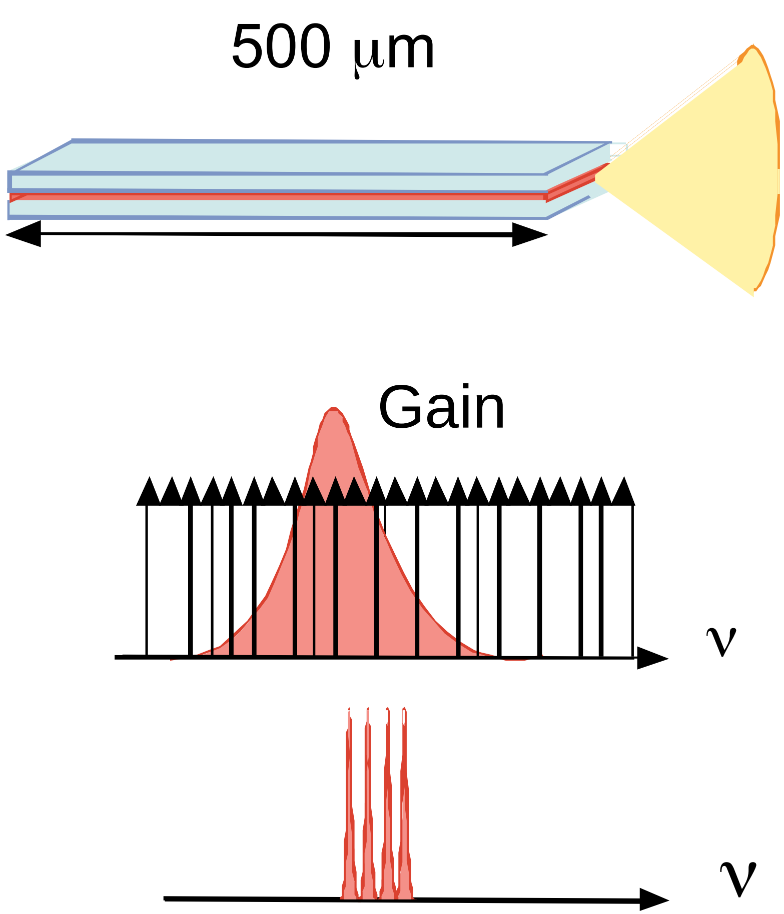


DFB laser characteristics

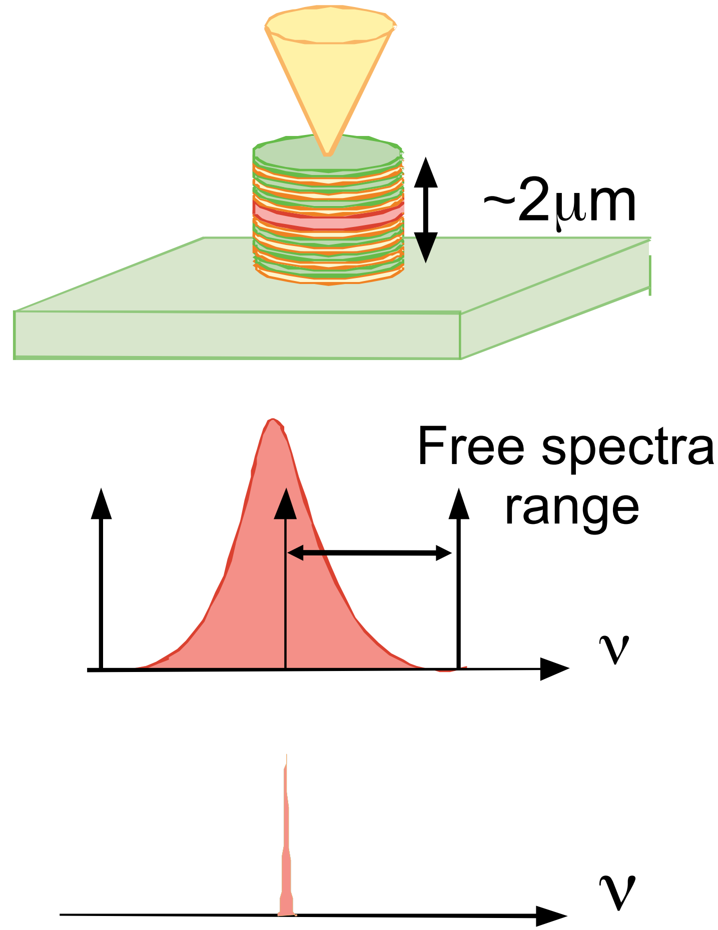
Tuning range	2 nm
Optical power	10- 100 mW
Spectral width	10^{3} - 10^{4} Å
Threshold current	10 mA

Semi-conductor laser structures

Edge emitters

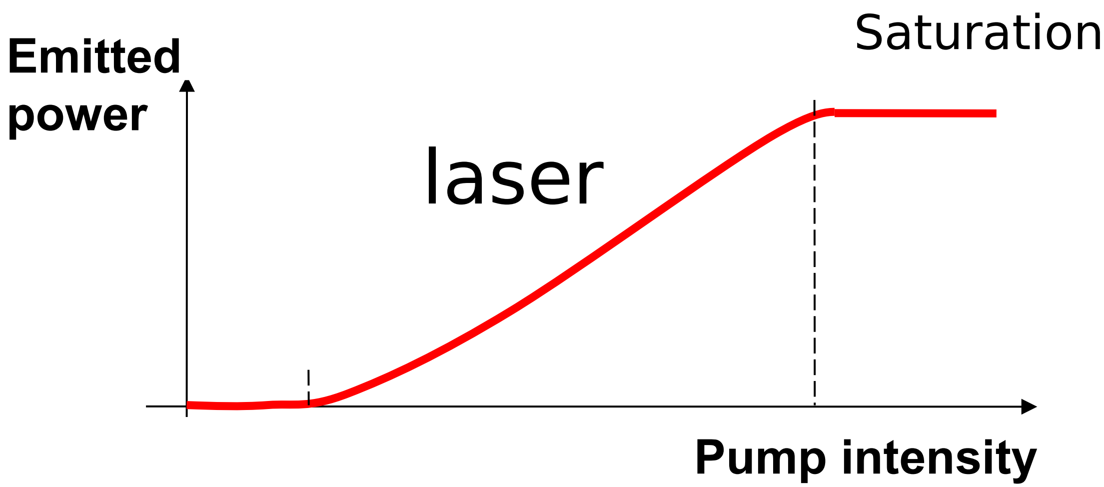


VCSEL
(vertical cavity surface emitting lasers)

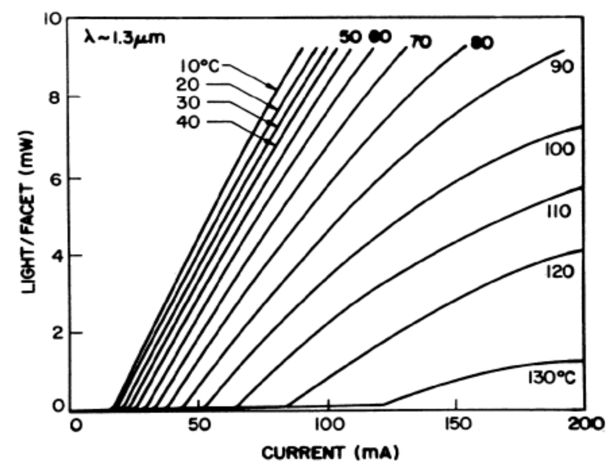


Emitted laser power characteristics

- Laser output power not proportional to drive current – threshold current exists
- When directly modulated – laser is used in the linear part of the curve
- BUT changing the drive current, changes the carrier (electrons/holes) density in the semiconductor which changes the refractive index causing wavelength shifts and broadening the spectral width.
- This effect limits direct modulation to < 2.5Gbit/s



Temperature dependence of laser characteristics:

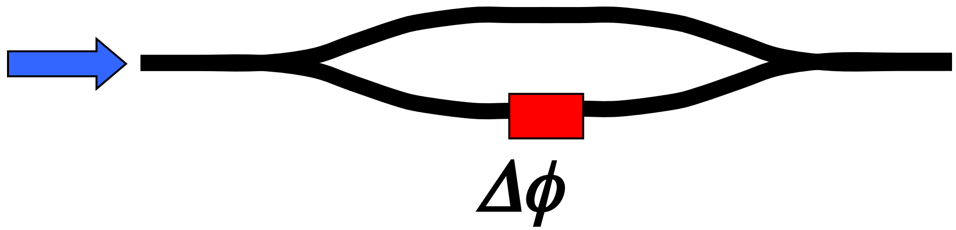


External modulation

- **For high datarates laser is unmodulated**
  - stable drive current, continuous optical output power
- **Data is modulated onto the optical beam with a second device**
- Examples of external modulator technologies
  - Lithium Niobate modulators (interferometric)
  - Electro-absorbing modulators
  - Acousto-optic modulators
  - Electro-optic modulators
  - Spatial Light Modulators (Liquid Crystal, MEMs etc)

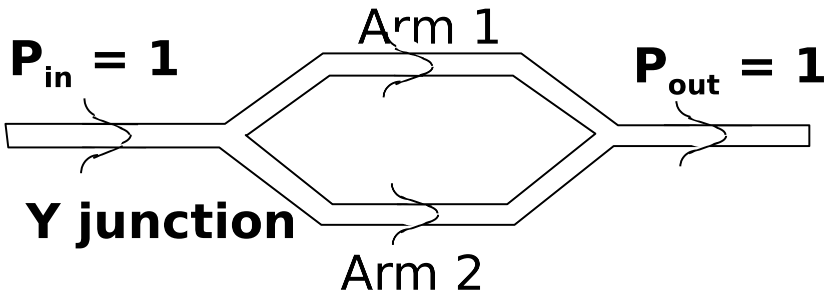
Operation of a MZ interferometer

Waveguide MZ :

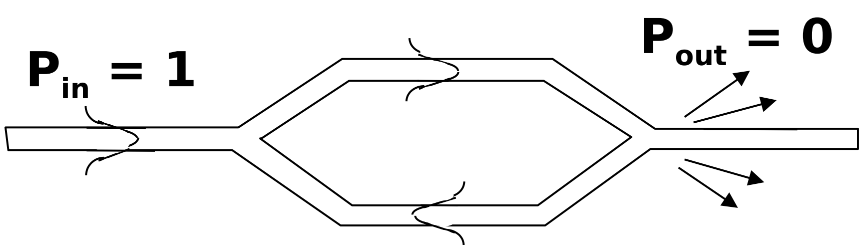


$$I = I_0 \cos^2\left(\frac{\Delta\varphi}{2}\right)$$

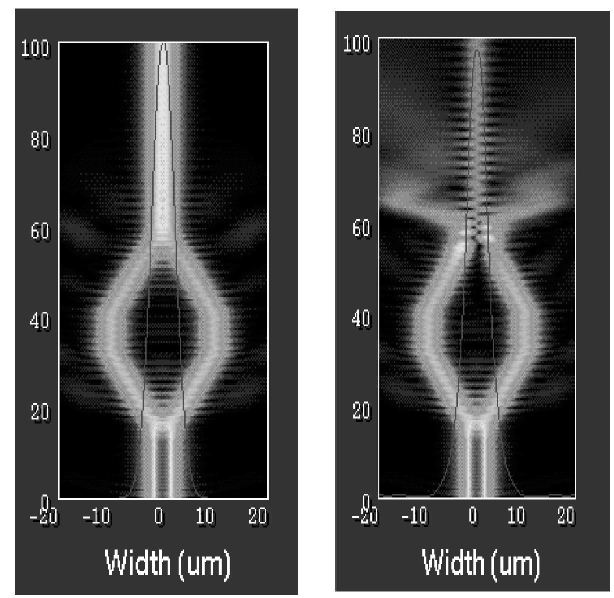
$\Delta\phi = 0$



$\Delta\phi = \pi$



Simulation of a MZ



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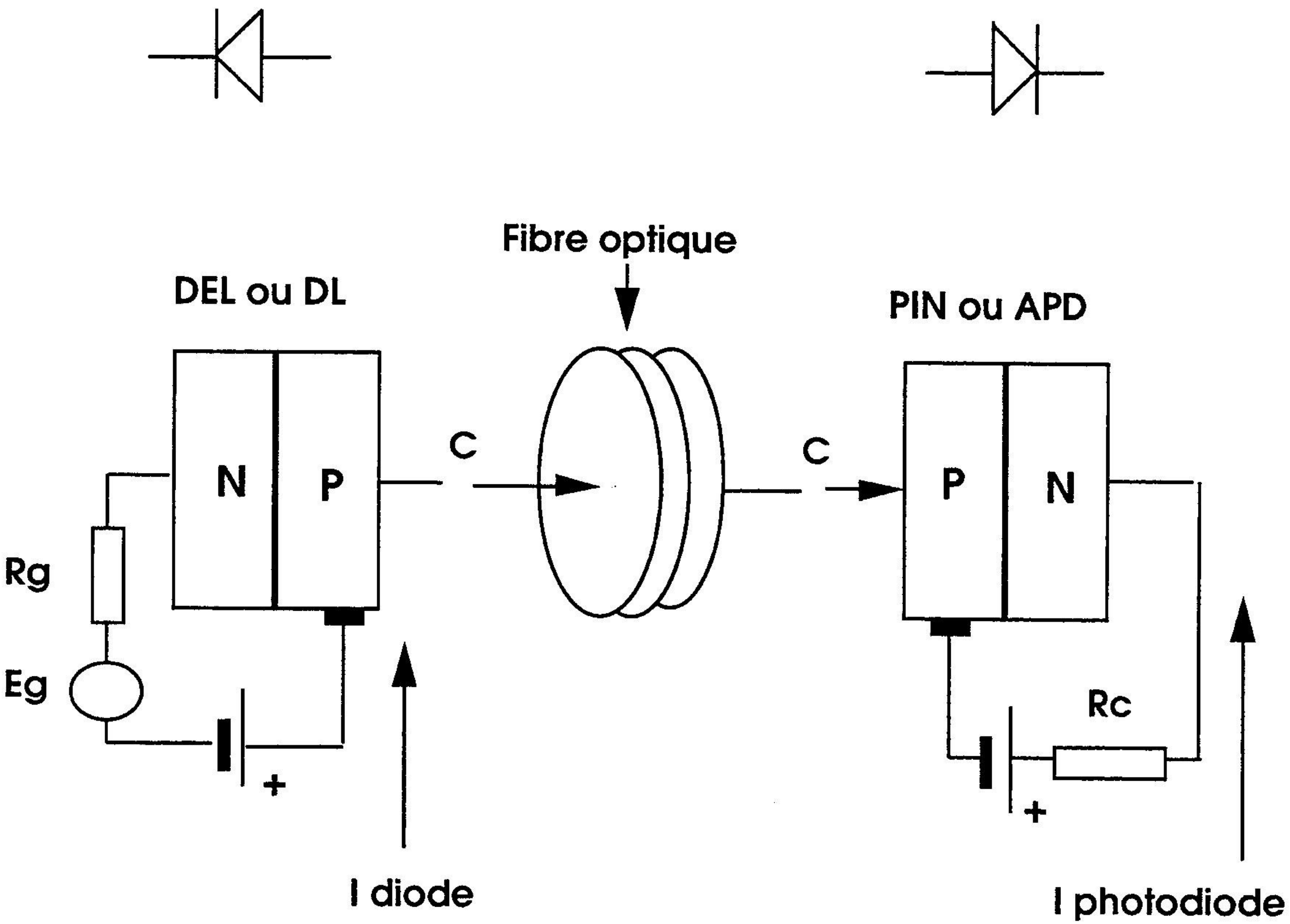
P-N junctions: opto-electronic convertors



Light absorption by semi-conductors

Light absorption is the reverse effect of light emission : an incident photon creates a free carrier pair (electron-hole) by removing an electron from its atom (ionisation).

The photon must have enough energy so there is a maximum absorption wavelength is given by :

$$\lambda_c = \frac{h.c}{E_g} = \frac{1.24}{E_g(eV)}$$

- For $\lambda < \lambda_c$, the material absorbs photons.
- For $\lambda > \lambda_c$, the material is transparent.

Bandgaps of a few common materials

Position in the periodic table	Semi-conductor material	Bandgap type	Bandgap size (eV @ 300°K)	
IV elements	Si Ge	indirect	1,12 0,72	
Binary III-V compounds	GaP GaAs InP InAs	indirect direct direct direct	2,24 1,43 1,29 0,35	 **0,85 µm**
Ternary III-V Compounds	$Ga_xIn_{1-x}As$ $Ga_xAl_{1-x}As$	direct direct or indirect	1,43 à 0,36 1,43 à 2,13	**1,3 µm**
Quaternary III-V Compounds	$Ga_xIn_{1-x}As_yP_{1-y}$	direct	1,43 à 0,36	**1,5 µm**

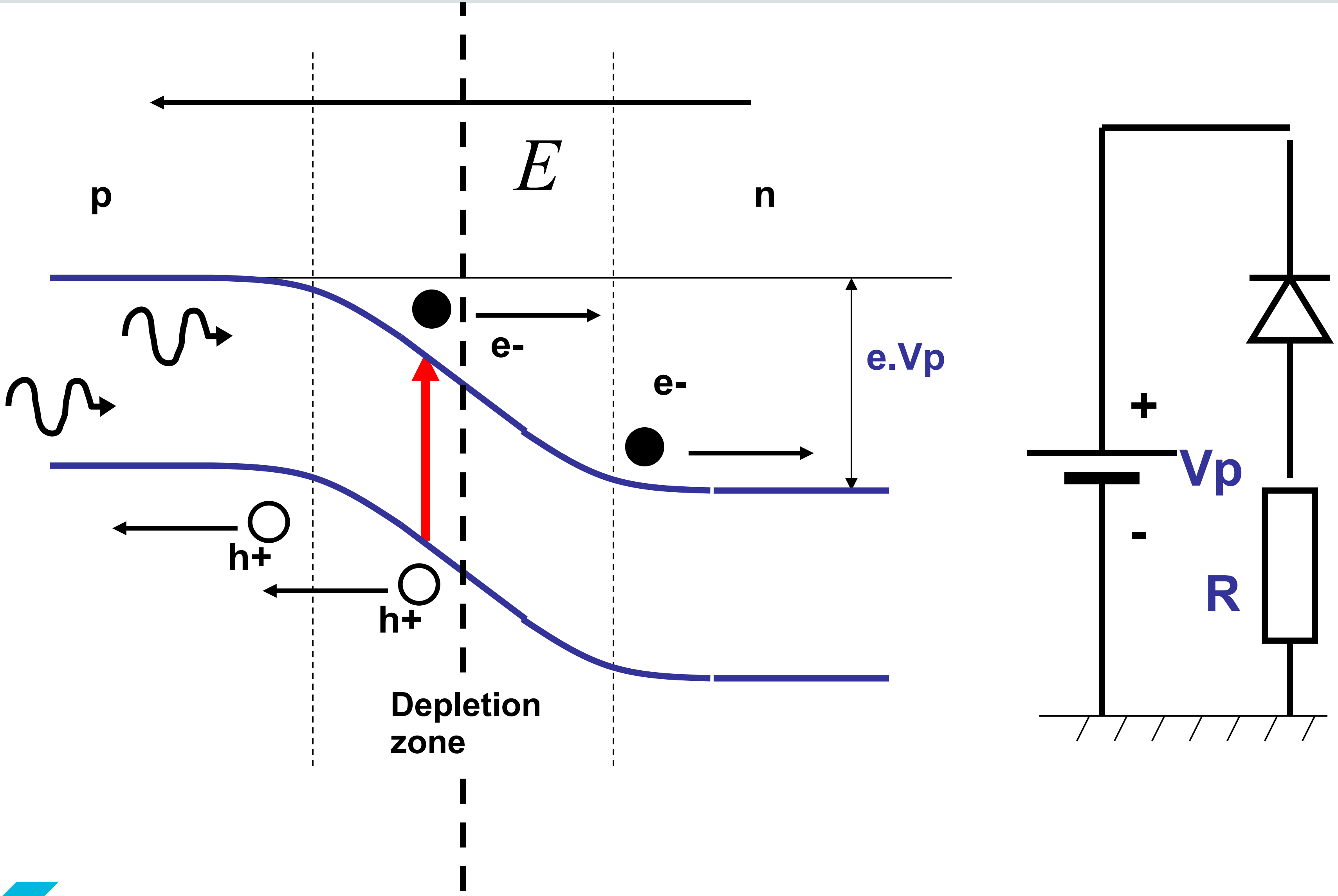
Photodetection at a semi-conductor junction

- **Absorption of a photon in a semi-conductor material creates an electron-hole pair if the energy of the photon is greater than the bandgap, E_g.**

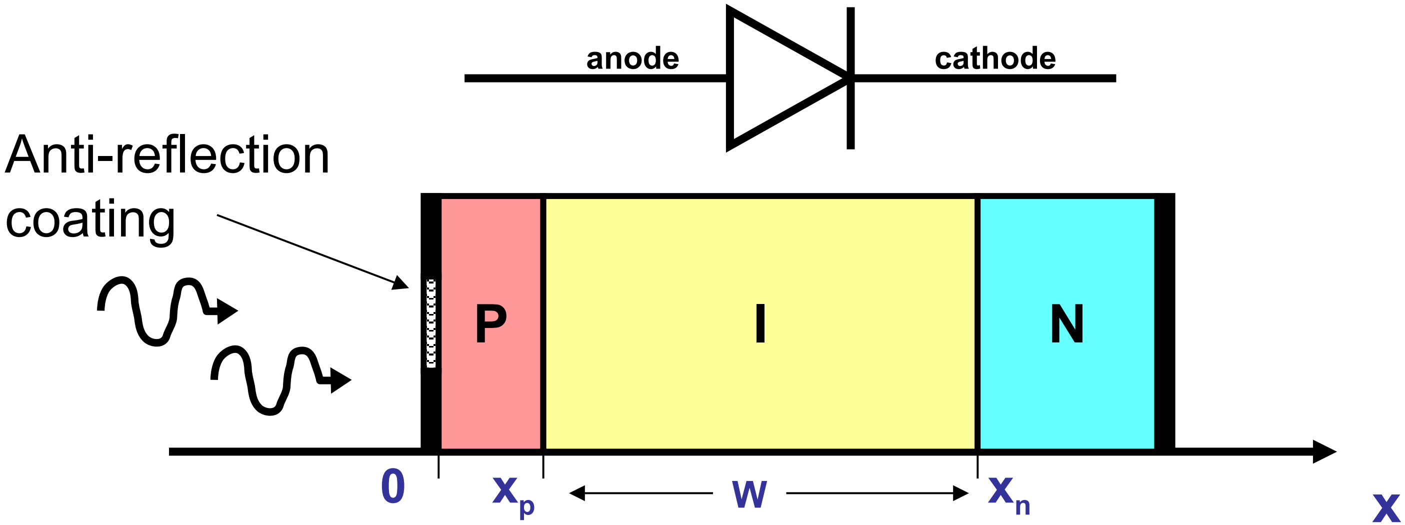
$$h\nu > E_g$$

- **To prevent recombination of this electron-hole pair, the photons must be absorbed in a zone containing <u>no free carriers</u>, for example the depleted zone of a P-N junction.**
- **To capture these photo-generated carriers as a photocurrent, they must be separated by a strong electric field.**
  - Reverse-biased junction.

Reverse-biased PN junction



The PIN photodiode

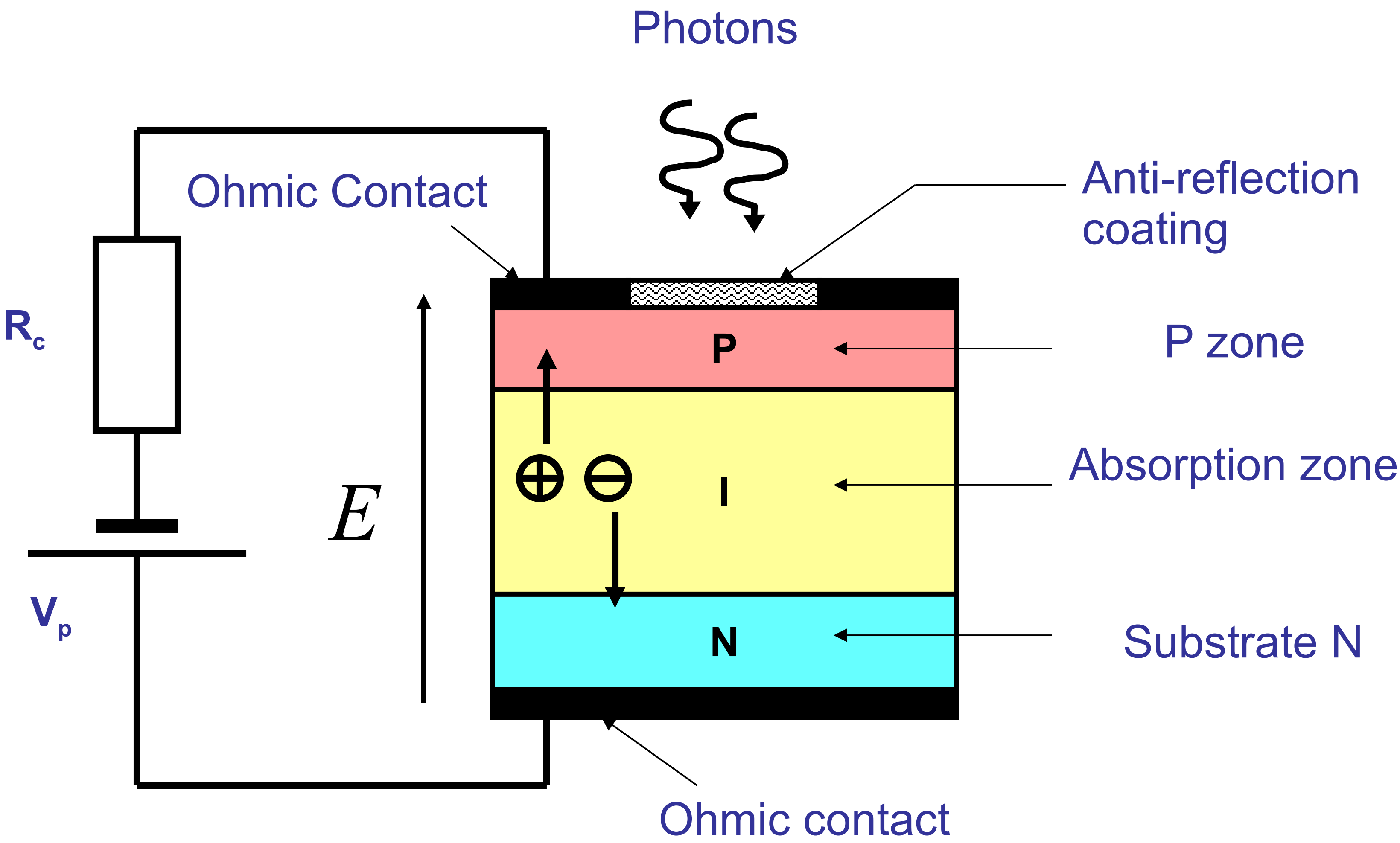


The insertion of a large intrinsic zone, I, containing no free carriers, between the P and N zones increases the photodiode efficiency.
Light absorption in the intrinsic zone is maximized by :

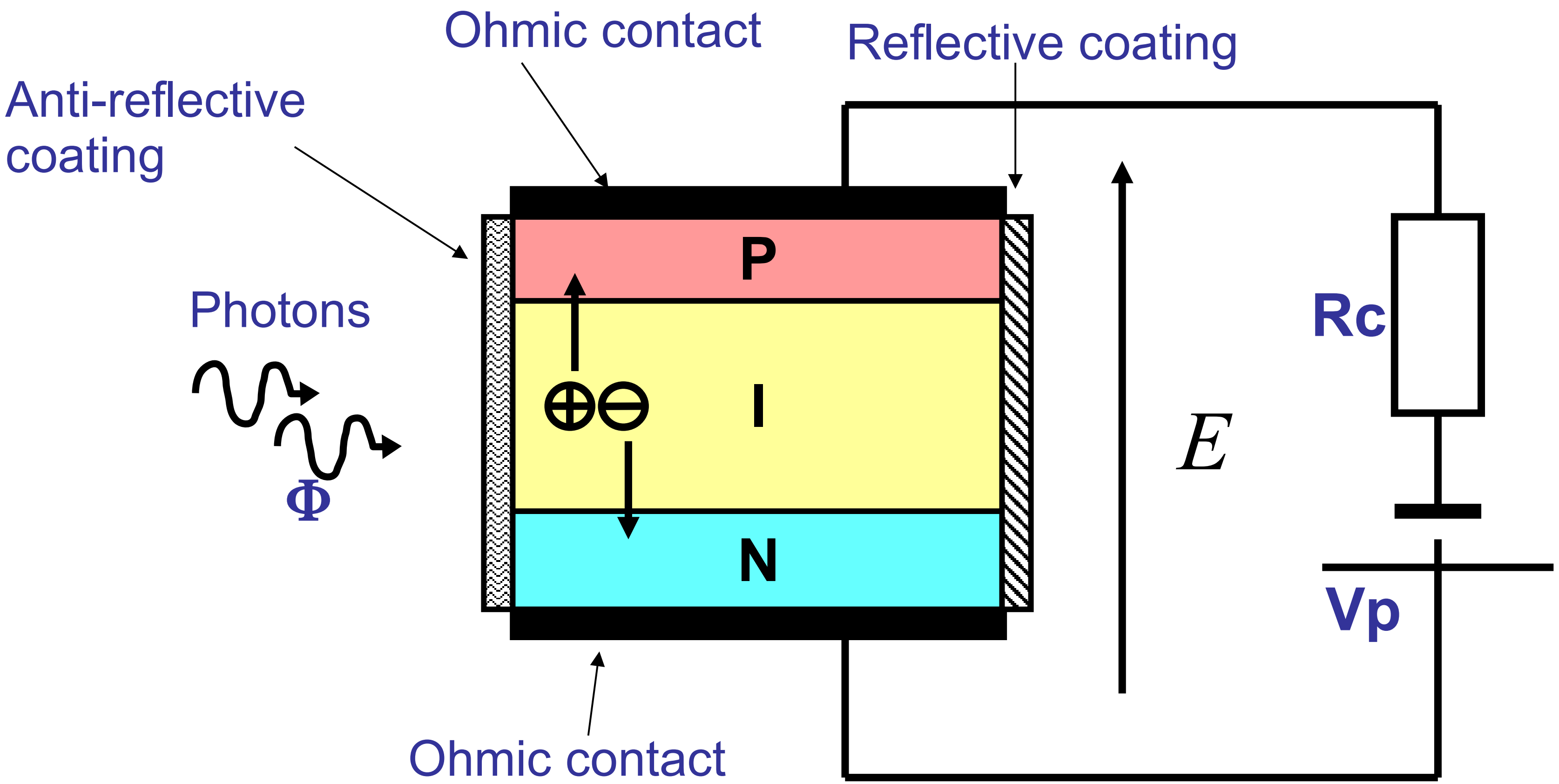
- coating the chip ends with an anti-reflection coating.
- use of a thin P zone and a low absorbance N zone.
- a sufficiently thick I zone (but not too large as this increases the transit time and hence the photodiode response time.

Efficiency – bandwidth tradeoff.

Standard configuration : top-illumination



Side-illumination



Advantages: improved absorption efficiency for a given I zone, fewer losses.
Drawbacks: fibre-photodiode coupling more difficult

Power – current relationship: sensitivity

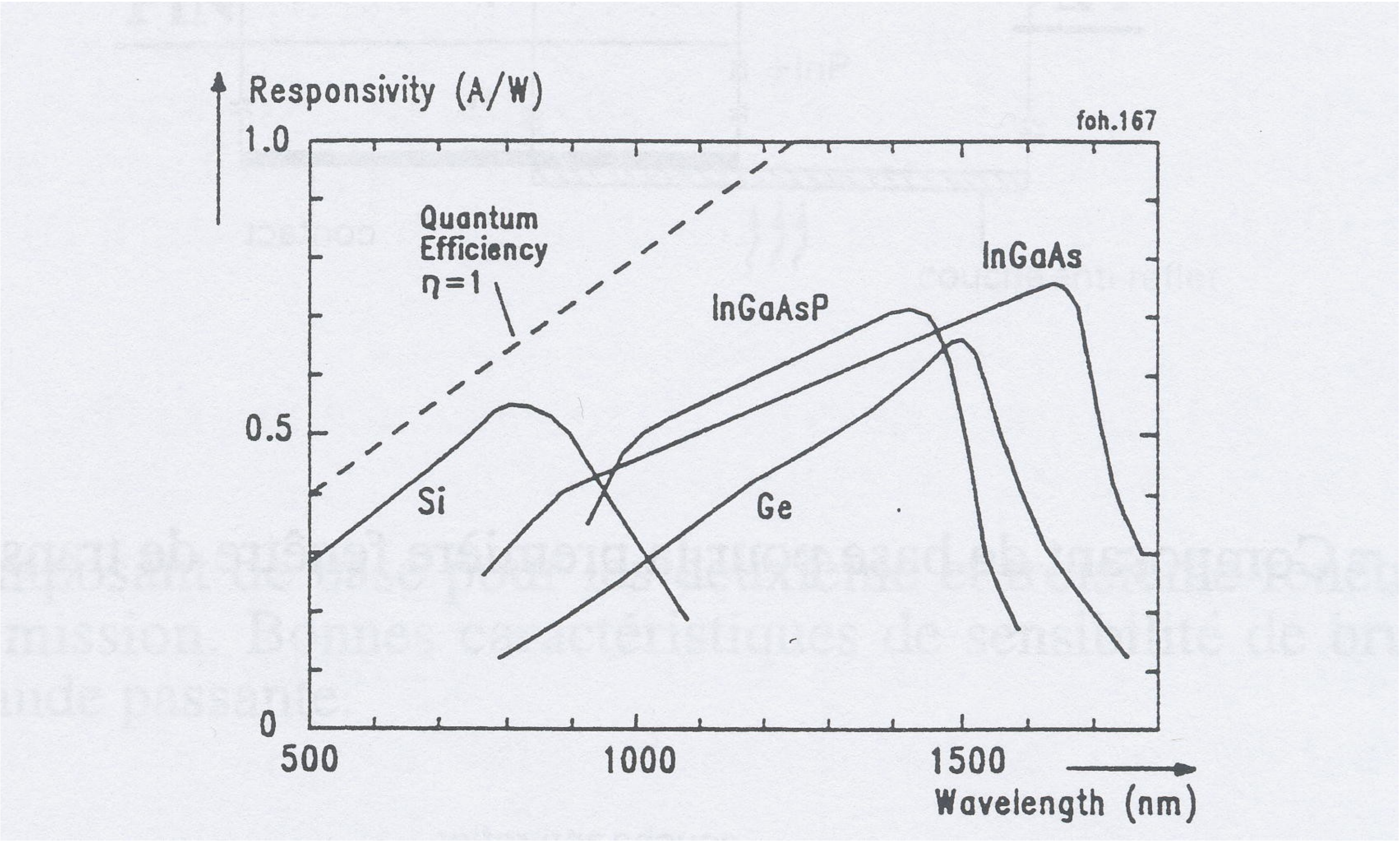
- The detection of an average optical power, P, at wavelength, λ, corresponds to the absorption by the photodiode of $P/h\nu$ photons per second.
- If the probability of the creation of an photocurrent electron-hole pair is η_{ext}, the diode collects $\eta_{ext}P/h\nu$ electrons per second, giving a photocurrent of:

$$I = e \cdot \frac{\eta_{ext} P}{h\nu} = \frac{\eta_{ext} e}{h\nu} \cdot P = S \cdot P$$

The coefficient S is called the "responsivity" of the photodiode (units A/W). In general, 0.5<S<1

<u>The photodiode is sensitive to the received light field intensity.</u>

Quantum efficiency of different materials



Dark current

- **Even in the absence of illumination, a low intensity current, called the "dark current", is present in a reverse biased photodiode.**
- **This leads to noise in the detected signal.**
- **The dark current is the sum of several currents including :**
  - a surface current linked to charges trapped at the metal/semi-conductor interfaces.
  - A volume current resulting from charges linked to material impurities.
  - A tunnel-effect conduction current occurring when the reverse bias is high and the bandgap is small
- **The dark current is strongly temperature dependent.**

Avalanche photodiodes (APD)

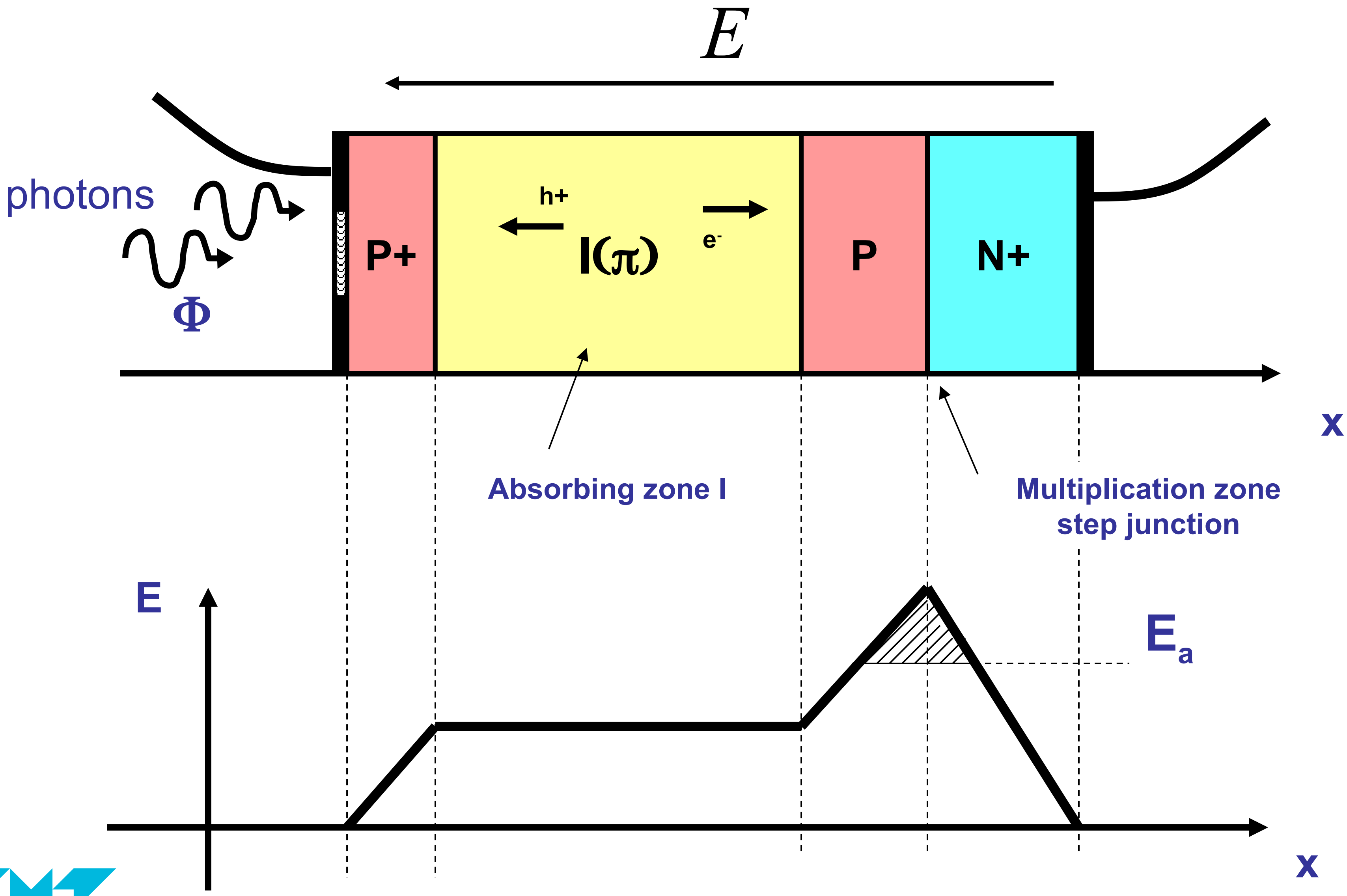
- Above a certain reverse-bias voltage, V_a, called the "avalanche voltage", the kinetic energy of the accelerated carriers is sufficient to ionise the SC crystal atoms by collision, therefore creating new free carriers.

Initiation of an "avalanche" phenomenon

- An incident photon no longer creates one free carrier pair but M pairs (on average). The coefficient M is called the <u>multiplication factor</u>.
- The photocurrent is now given by :

$$I_{ph} = M \cdot S(\lambda) \cdot P_{opt}$$

Standard APD structure : PπPN diode



APD multiplication factor

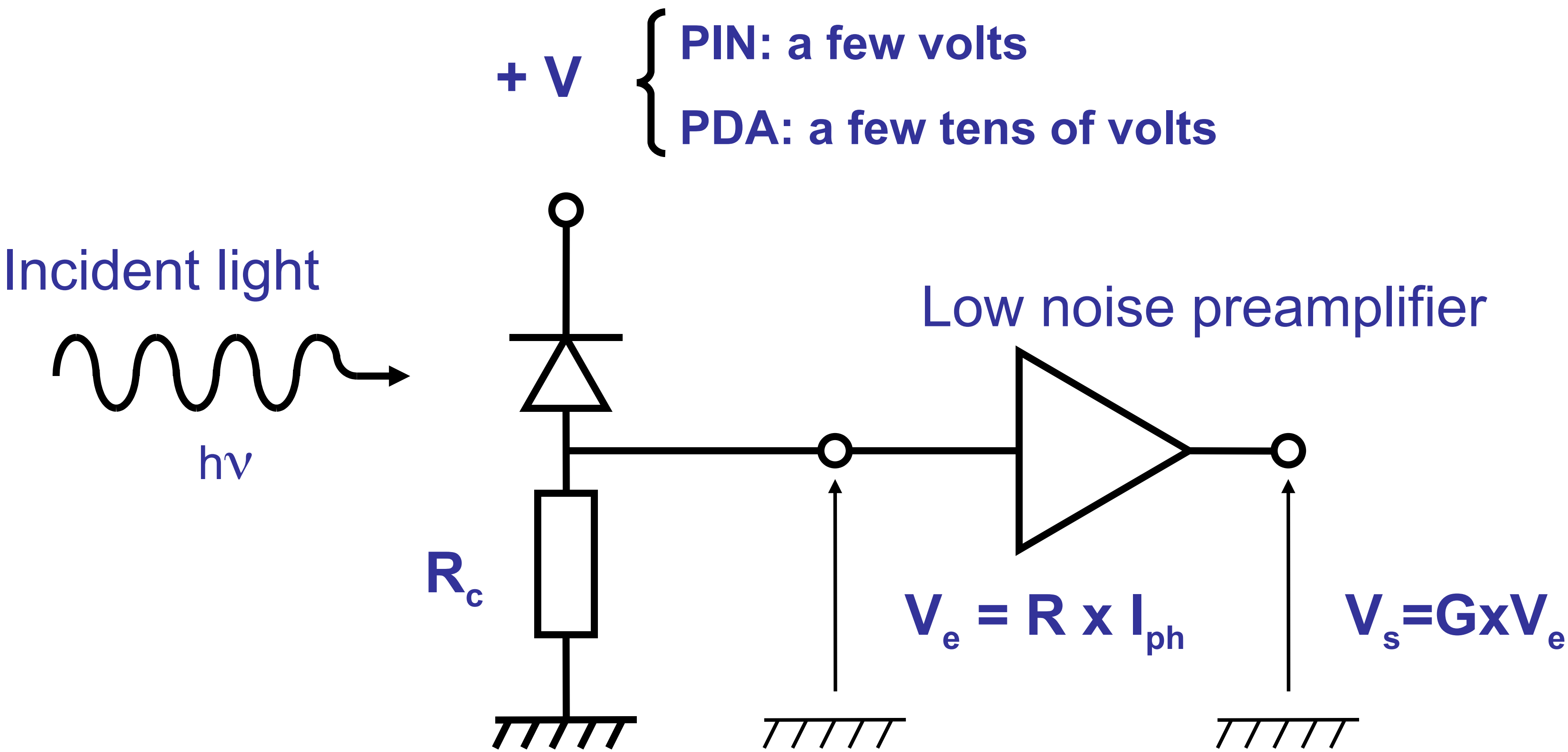
- **M increases with the reverse-bias voltage, V_{polar}**
- **M decreases with temperature.**
- **High reverse bias :**
  - Si: 500V
  - Ge: 30 V
  - Multiplication factor M:
    - Si: M=100
    - Ge: M=10
  - Device characterized by the gain-bandwidth product MxB. M.B >> 200 GHz
  - In general, the bandwidth decreases for increasing M.
- **Although the avalanche phenomenon produces high internal device gain it is also a noisy effect. APDs are therefore naturally noisier than PIN photodiodes.**

Gain – Noise trade-off

Practical use of photodiodes

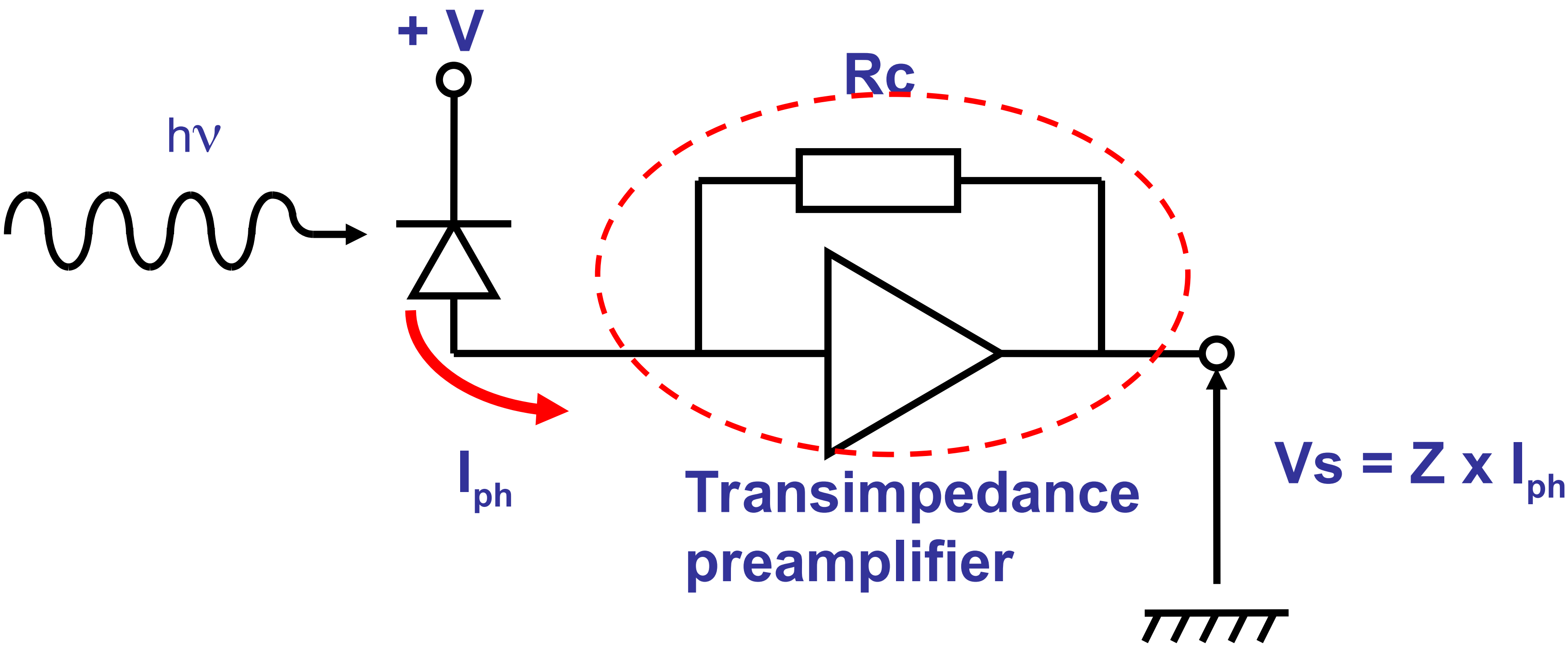
- **A complete optical receiver includes :**
  - The photodetecting diode and its coupling optics.
  - The circuit for reverse-biasing the photodiode.
  - The amplification circuit matched to the detected signal with its corresponding drive circuit.
  - In some cases - filters.
- **The receiver must be matched to the signal to be detected:**
  - For minimum (responsivity) and maximum (saturation) signal levels
  - For bandwidth.
  - For signal to noise ratio.

Matched optical receiver



Transimpedance optical receiver

Integrated PIN-FET or APD-FET detectors



- Converts current signal to voltage signal with amplification
- Z: transimpedance (in Ω or dBΩ) feedback to the amplifier : better noise-bandwidth compromise

LECTURE PLAN :

- Solid state physics refresher
- Spontaneous and stimulated emission
- Light Emitting Diodes
- Laser Diodes: Fabry-Perot and DFB
- Photodiodes : PIN and APD
- Detection noise: thermal, quantum, amplifier

Quantum (“shot”) noise.

- Quantum or “shot” noise arises whenever a stream of particles is emitted in a random manner : inevitable random fluctuations in the average detected flowrate. Example: the sound of raindrops on a window.
- Electromagnetic radiation and electrical current are streams of particles - “quantums” (respectively photons and electrons).
- Quantum noise is therefore inherent to matter and radiation.
- It can be shown that the emission of photons in electromagnetic radiation and of electrons in electrical current follow Poisson law statistics.

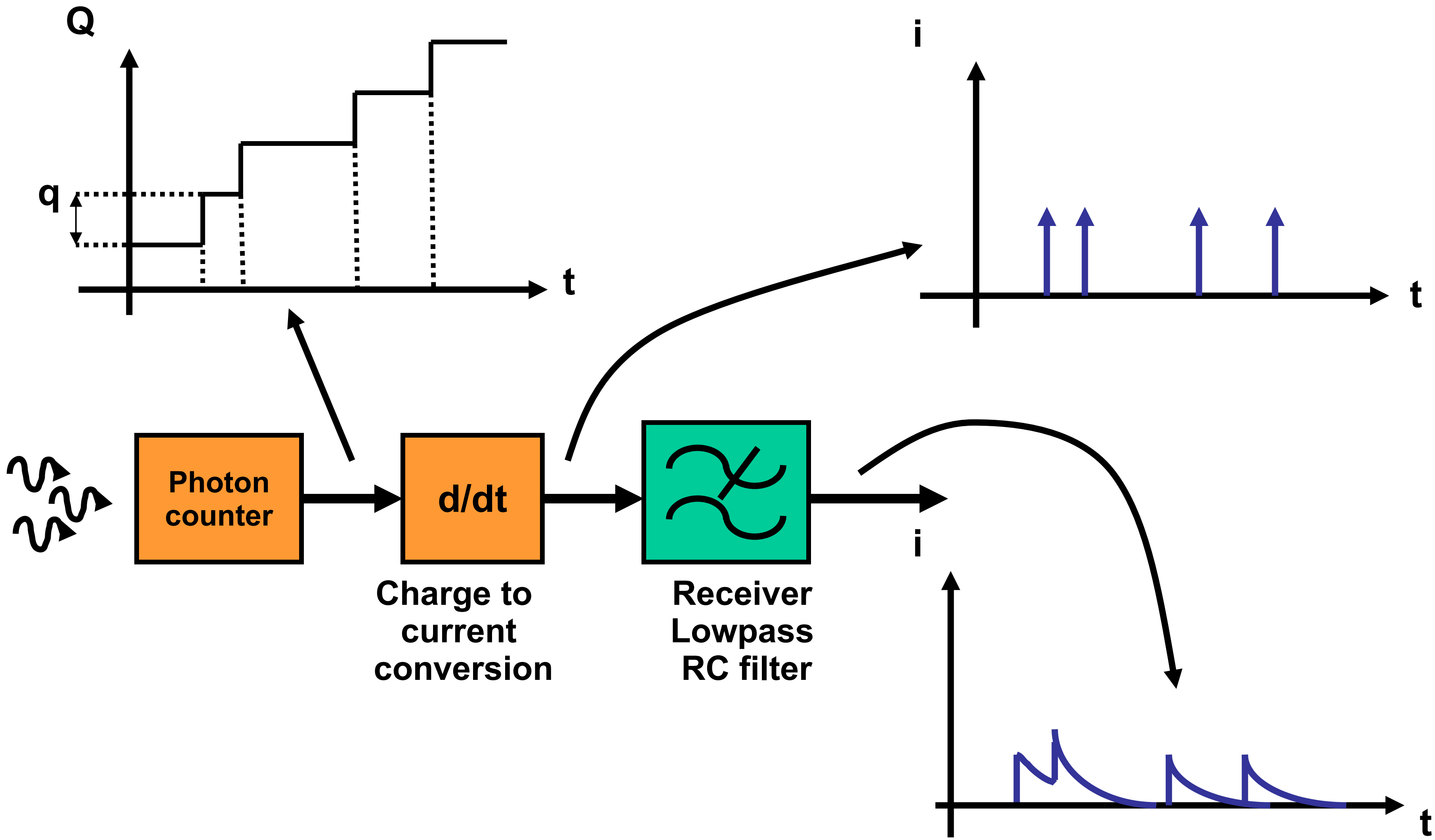
Poisson law statistics of quantum noise.

- For a flow of particles obeying Poisson law statistics, the probability of observing N particles in a given time, T, is given by :

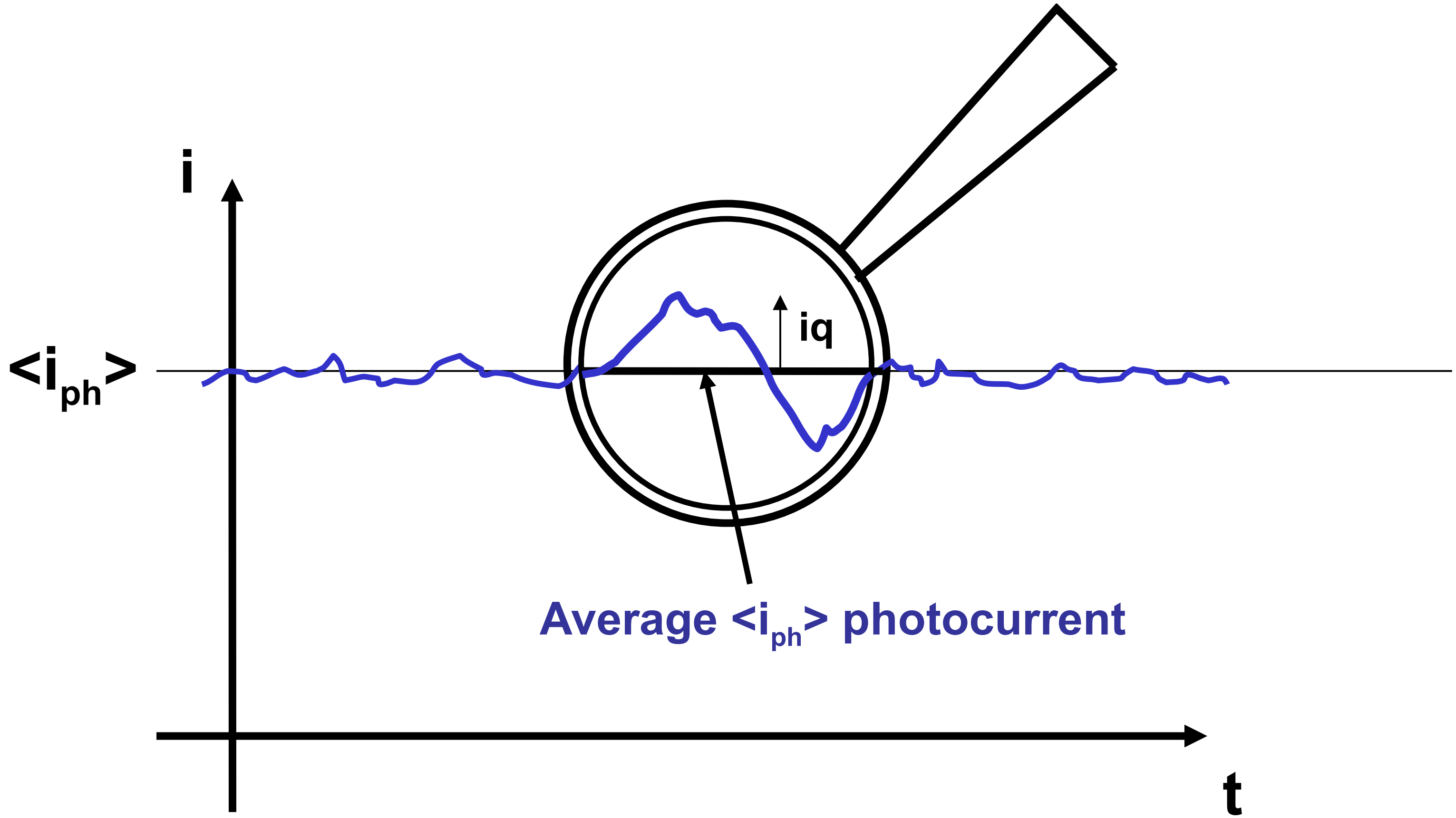
$$Pr(N) = \frac{(\lambda T)^N \exp(-\lambda T)}{N!}$$

- The coefficient, λ, is called the process density, it represents the average number of particles observed in unit time.
- When λ increases, the Poisson distribution tends towards a Gaussian (or Normal) distribution.

From photon counter to real receiver



Photocurrent under the microscope …



Written : $i_{ph} = < i_{ph} > + i_q = SP_{opt} + i_q$ **with** $< i_q > = 0$

Random component of the photocurrent

Quantum noise

- Quantum noise is added on top of the continuous photocurrent.
- Quantum noise is thus a centred (zero-average) Gaussian distributed white noise ("flat" spectrum). Its power is given by:

$$< i_q^2 > = 2 e I_{ph} \cdot \Delta f$$

- For an avalanche photodiode, this noise power is multiplied by a factor M^{2+X} which takes avalanche noise into account.
- The $F(M)= M^X$ coefficient is called the "excess noise factor".

Thermal (or Schottky) noise

- This noise arises from the thermal agitation of carriers in the conducting medium. It is particularly significant in resistors and transistors at room temperature.
- The thermal noise current has a zero average value. Its mean square value (power), $\langle i_{th}^2 \rangle$, is given by :

$$\langle i_{th}^{2} \rangle = \frac{4\,kT \cdot \Delta f}{R_c}$$

- For all electronic applications thermal noise is considered to be white. It obeys Gaussian law statistics and is <u>specific to each receiver.</u>

Post-detection signal to noise ratio

At the preamplifier output, the signal to noise ratio, in its most general form, can be written as :

$$SNR = \frac{\left(MI_p\right)^2}{\frac{4kT \cdot \Delta f}{R_c} + 2e\left(I_p + I_d\right) \cdot \Delta f \cdot M^{2+x} + \langle i^2_{amp} \rangle}$$

I_p	: photocurrent
I_d	: dark current
i_{amp}	: preamplifier noise current
M	: Multiplication factor (1 for PIN diodes)
X	: excess noise factor (0 for PIN diodes)

Conclusion

- Basic solid-state physics of sources/detectors
  - Energy levels and energy bands
  - Spontaneous and stimulated emission
- LED: spontaneous emission, uncollimated, wide spectrum, cheap ...
- Fabry-Perot laser : LED in a cavity, directive, lower spectral width, cheap ...
- DFB, DBR and VCSEL lasers include a (Bragg) wavelength selective section for very low spectral width and high performance
- Direct modulation of semiconductor lasers up to ~1Gbit/s
- External modulation for high performance (10Gbit/s) systems
- Basic photodiode operation: pn junction, photon → charges
- Differences and advantages/disadvantages of PIN and APD photodiodes
- Thermal and Quantum noise.

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