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# Optoelectronics

## part1

M2 Nanosciences: nano-dispositifs  
M2 Composants et Antennes pour les Telecoms  
M2 Réseaux Optiques & Systèmes Photoniques

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# Plan

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- Semiconductor Lasers (1):
  - I. Diode laser: Inter-band transition (Near Infrared)
  - II. Quantum cascade laser: Inter sub-band transition (Mid Infrared)
- Mid Infrared Detectors (2)
  - III. Inter sub-band detectors: QWIP (Quantum Well Infrared Photo detector)
- 2 class with F. Grillot
  - Lab work (X. Chécoury, A. Bousseksou)
  - Journal club (X. Chécoury, A. Bousseksou, F. Grillot)
  - Exam (You folks!).

# Semiconductor lasers:

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## I. Diode lasers

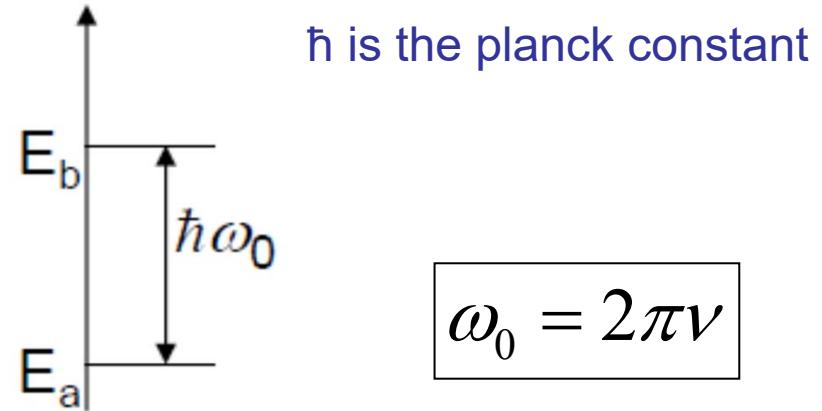
- I.1 light-matter interaction: Optical transition in semiconductors
- I.2 Semiconductor lasers (Inter-band transition ): bulk SC, Quantum wells.
- I.3 III-V semiconductors, wavelength selection,
- I.4 Diode laser applications: wavelength multiplexing, III-V on Silicon...

## II. Quantum cascade lasers

- II.1 Introduction: Mid Infrared photonics, motivations.
- II.2 Associated technologies: Growth, fabrication.
- II.3 State of the art
- II.4 Quantum cascade laser: Laser waveguide, active region, mode control
- II.5 Laser characterization
- II.6 QCL in research: QCL as Surface plasmon polariton source

## I.1 light-matter interaction

- A two level system:  $E_a$  et  $E_b$
- Electrons can emit or absorb a photon with «  $\omega_0$  » pulsation (pulsation de Bohr)



$\hbar$  is the planck constant

$$\omega_0 = 2\pi\nu$$

$\nu$  is the frequency

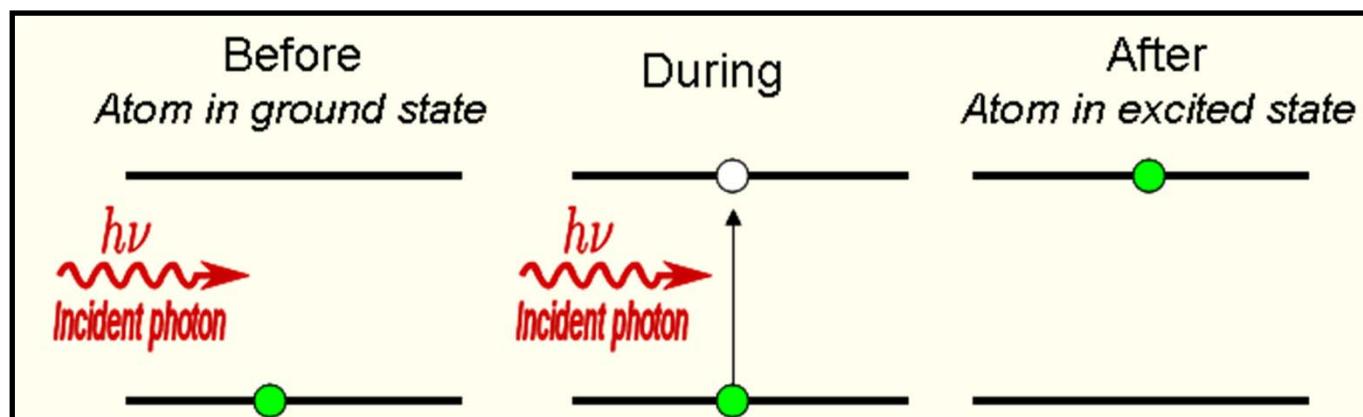
An electromagnetic wave is a perturbation of the system.

The interaction de electromagnetic wave with the quantum two level system makes the electrons jumps between stationary states ( $E_a$   $E_b$ )

# I.1 light-matter interaction : Absorption

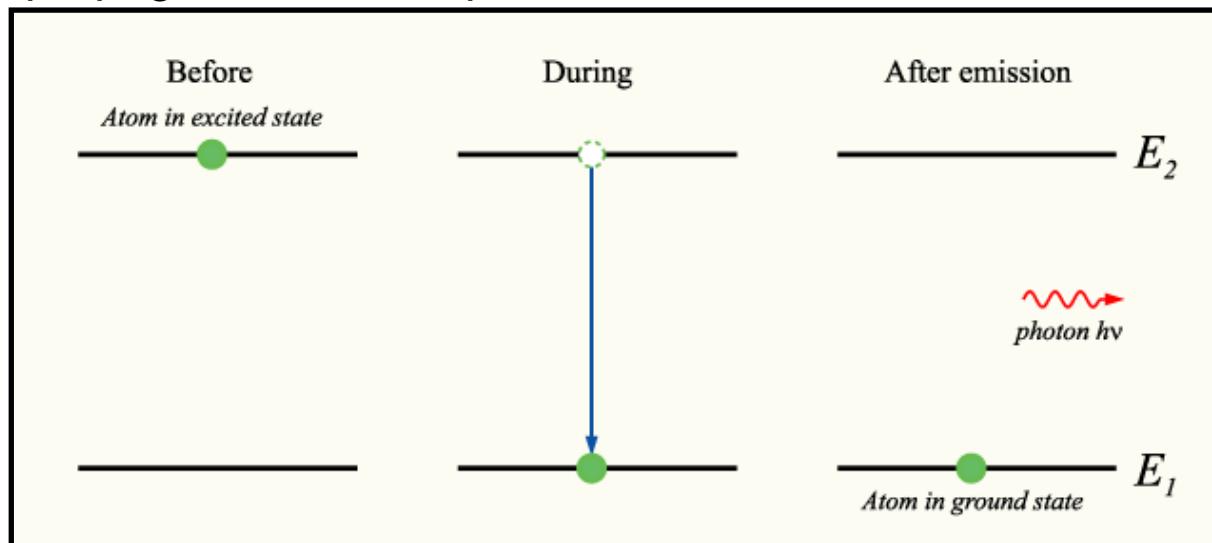
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- Initially the electron is in the ground state (fundamental state)
- Incident photon can be absorbed, the absorbed energy allows an electron in the ground state to go on the excited state.



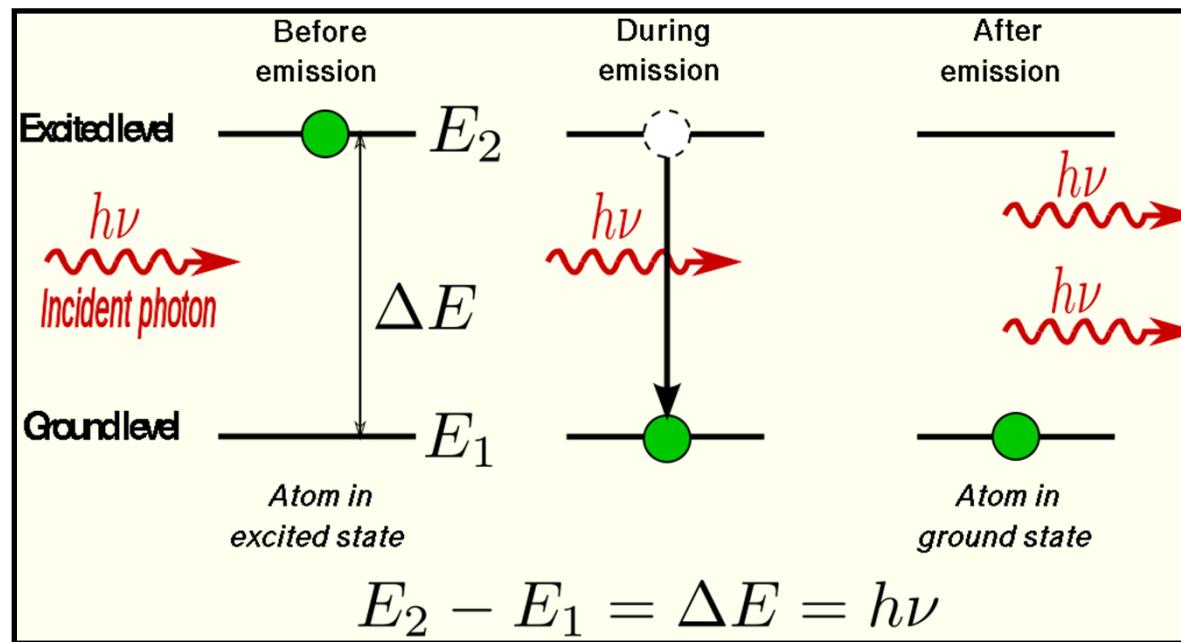
# I.1 light-matter interaction : Spontaneous emission

- The system is initially on the excited state (after absorption phenomenon for instance)
- The electron can go back to the fundamental state loosing energy by emitting a photon. This is the spontaneous emission.
- The emitted wave has a frequency equal to the Bohr radiation  $\omega_0$ , the direction of propagation and the phase are random.



# I.1 light-matter interaction : Stimulated emission

- The emitted photon is identical to the incident photon (pulsation, phase, direction)



**When the optical transition occurs:**

- Energy conservation
- Wave vector conservation

# I.1. Optical transitions in a semiconductor

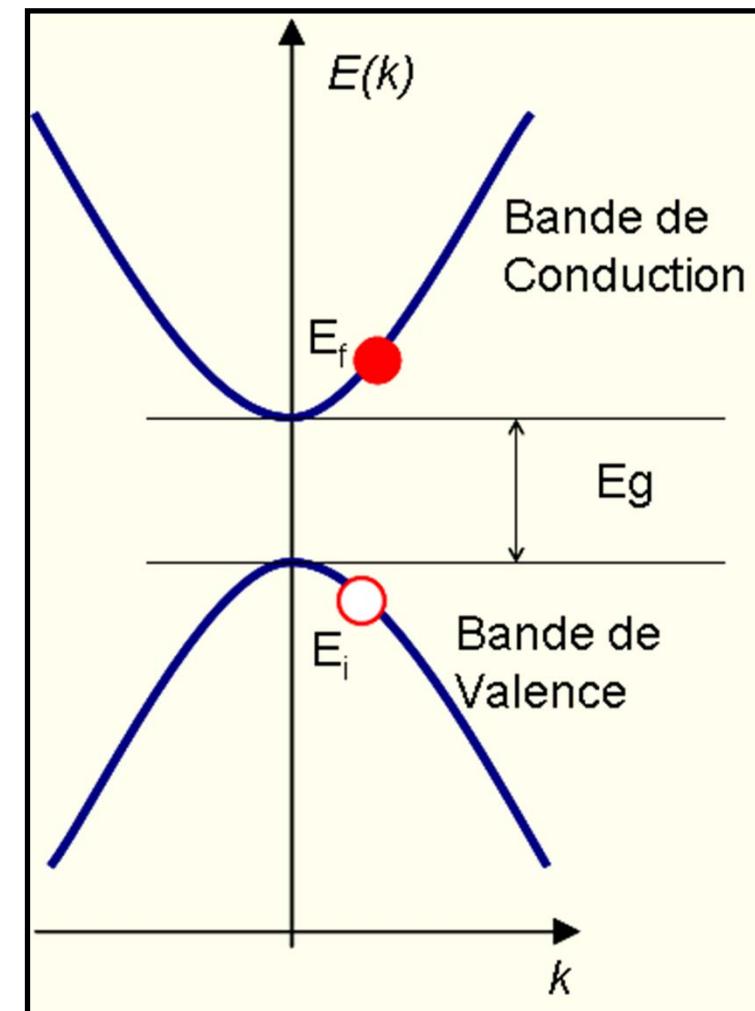
## Stimulated emission / absorption :

- Conservation of energy and conservation of wave vector

$$E_f = E_i \pm h\nu$$

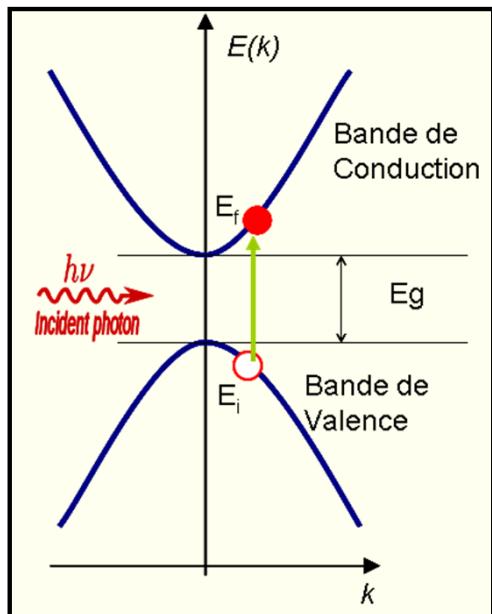
$$k_f = k_{\text{photon}} \pm k_i$$

$k_f, k_i \gg k_{\text{photon}}$  it means that  $k_f \sim k_i$  :  
The optical transition are mainly « vertical » in the photonics band diagram

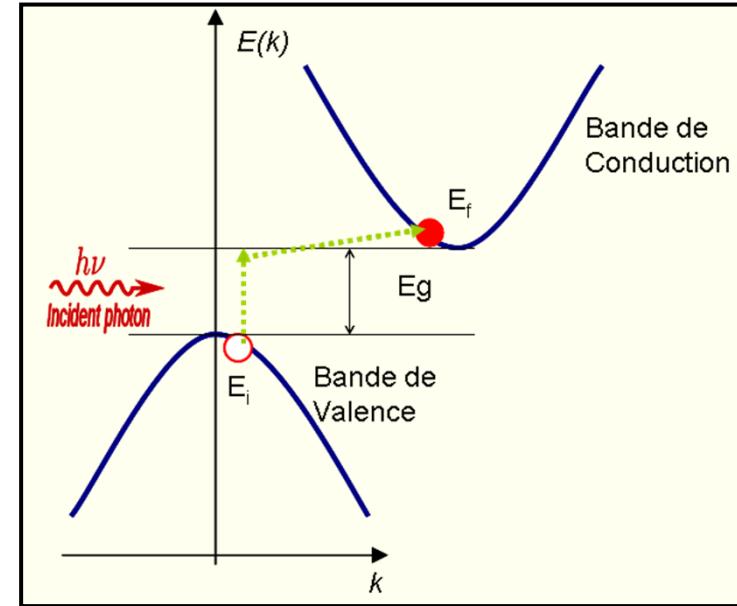


# I.1. Absorption in semiconductor

## Direct band gap semiconductor



## Non-direct band gap Semiconductor



$$h\nu \approx E_g$$

$$\frac{hc}{\lambda} \approx E_g$$

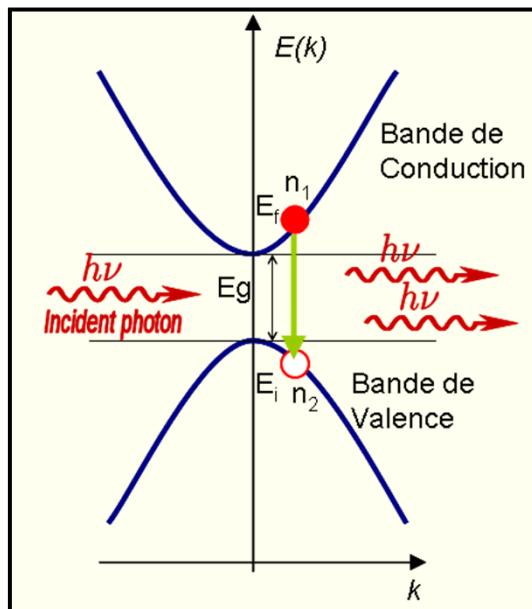
Where "c" is the light velocity  
"λ" id the wavelength

$$\lambda [\mu m] \approx \frac{1.24}{E_g}$$

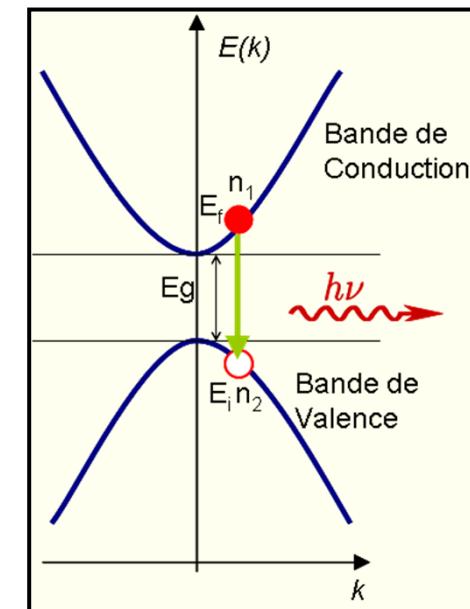
- The transition can occurs when “something” can permit the wave vector conservation = “**phonon**”
- The probability of optical transition is much less than in the direct band-gap system.

# I.1. Emission dans un direct gap semiconductors

Stimulated emission



Spontaneous emission



- dual mechanism of absorption
- Optical amplification
- The probability is much more higher if the electron population (carrier population) in the conduction band is higher than population in the valence band ( $n_1 > n_2$ )
- .

Light emitting diode based phenomenon

Laser diode based phenomenon

## I.1 Génération / recombinaison des porteurs libres

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- Absorption is a mechanism that **generates** free carriers in the semiconductor
- Emission is a mechanism that **recombines** free carriers in the semiconductor

Others mechanism for carrier generation:

- Thermal generation
- Carrier injection (electrical diode polarization )
- Ionisation impact

Non radiative recombination :

- Auger Recombination
- Interface and surface recombination.
- Defects recombination

## I.1 Carrier life time

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- Recombination rate of carriers "R<sub>n</sub>"

$$R_n = \frac{dn}{dt} = \frac{-\delta_n}{\tau_n}$$

$\delta_n$  Is the variation of the concentration of carriers at the equilibrium

$\tau_n$  Is the carrier lifetime « n type are electrons »

- Quantum efficiency " $\eta_i$ ":

$$\eta_i = \frac{R_R}{R_R + R_{NR}} = \frac{1}{1 + \frac{\tau_R}{\tau_{NR}}}$$

$\tau_R$  Radiative life time

$\tau_{NR}$  Non-radiative life time

## I.2 Semiconductor LASER

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**LASER = Light Amplification by Stimulated Emission Radiation**

A photon is emitted by stimulated emission is identical to the incident photon => laser coherence

- Three main conditions are mandatory to have laser emission:
  1. Gain medium, high quantum efficiency with high radiative recombination rate.
  2. Population inversion (pumping)
  3. Optical feedback (optical cavity)

## I.2 Semiconductor laser: Optical Oscillator

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- Laser = optical oscillator

As an electronic oscillation :

- Gain medium
- Pumping
- Cavity

*Configuration classique : laser à émission par la facette*

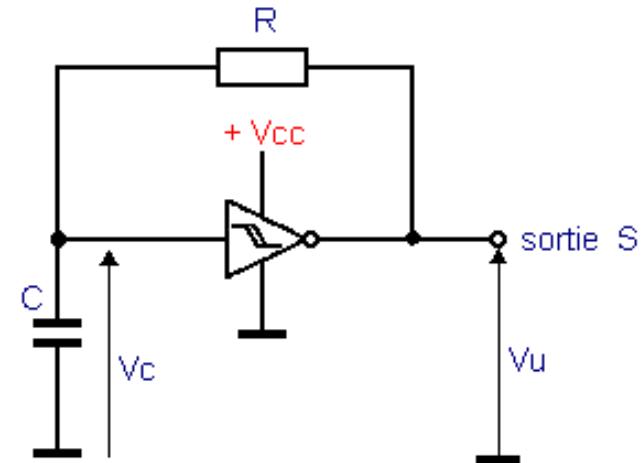
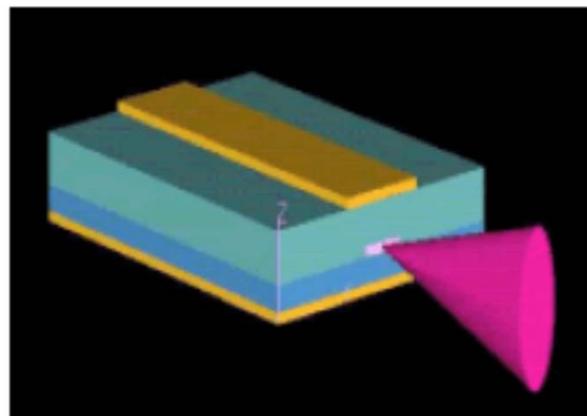


Fig. 44. - Oscillateur à trigger de Schmitt.

## 1.2 Condition for laser effect

- A simple optical cavity : two mirrors cavity Cavité Fabry-Pérot

$g$ =optical gain

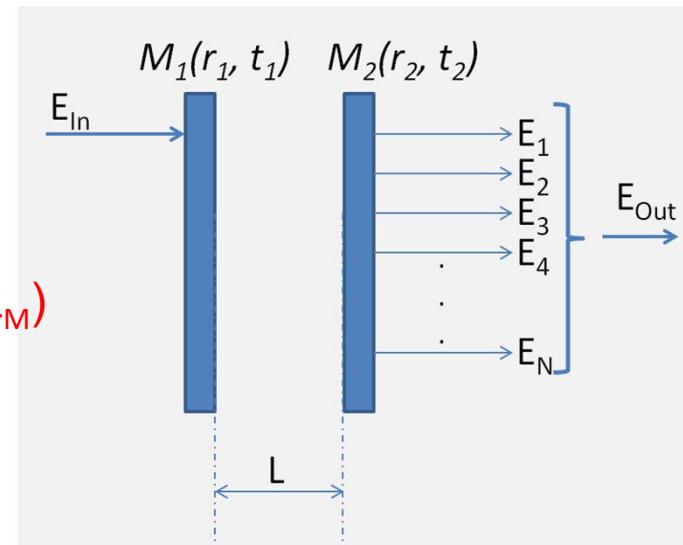
$\alpha$  = optical losses

- After one round trip **gain must recover losses**

Waveguide losses ( $\alpha_w$ )

$$g = \alpha - \frac{1}{2L} (r_1 r_2)$$

miroirs losses ( $\alpha_M$ )



- After one round trip **The phase must be the same:**

$$2\pi 2L/\lambda = 2\pi p$$

- Where  $p$  is an integer

## 1.2 Rate equations

$$\frac{\partial N}{\partial t} = -\frac{N}{\tau_p} + \Gamma g N \frac{c}{n_{opt}} + \Gamma \beta \frac{n}{\tau_R}$$

Spontaneous emission

$$\frac{\partial n}{\partial t} = \frac{j}{q \times d} - g N \frac{c}{n_{opt}} - \frac{n}{\tau_{TOT}}$$

Stimulated emission

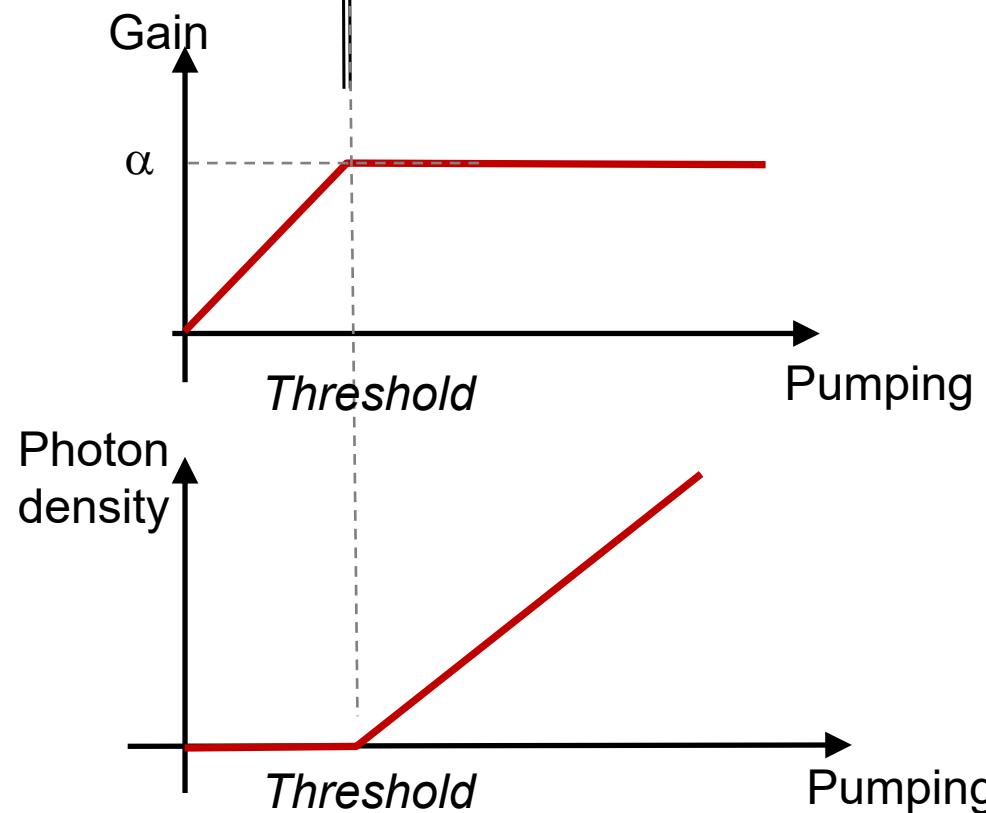
- $n, N$  are photon and electron density ( $\text{cm}^{-3}$ )
- $\beta$  est le facteur de réinjection des photons
- $g$  is the pumping gain ( $\text{cm}^{-1}$ ) :  $g = a(n-n_t)$
- $\tau_p$  is the photon life time the optical cavity
- $\tau_{TOT}$  is the total electron lifetime :  $1/\tau_{NR}=1/\tau_R+1/\tau_{NR}$
- $j$  is the injected current density
- $d$  is the thickness of the active region
- $\Gamma$  is the mode cofinement factor
- $\alpha$  are the waveguide losses ( $\text{cm}^{-1}$ )
- $n_{opt}$  is the optical refractive index

$$\frac{1}{\tau_p} = \frac{1}{\tau_i} + \frac{1}{\tau_{rad}} = \frac{c}{n} \alpha + \frac{c}{n L} \ln \left( \frac{1}{R} \right)$$

## 1.2 Rate equations

$$\frac{\partial N}{\partial t} = -\frac{N}{\tau_p} + \Gamma\beta \frac{n}{\tau_R}$$
$$\frac{\partial n}{\partial t} = \frac{j}{q \times d} - \frac{n}{\tau_{TOT}}$$

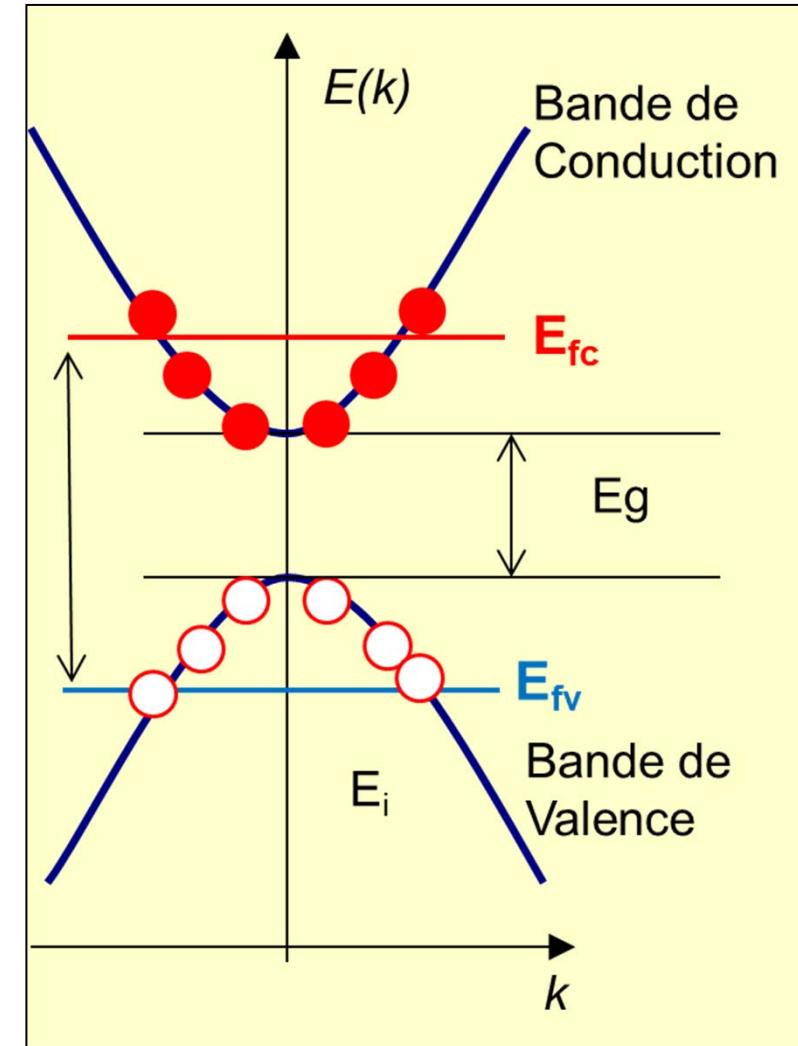
$$\frac{\partial N}{\partial t} = \left( \Gamma g \frac{c}{n_{opt}} - \frac{1}{\tau_p} \right) N$$
$$\frac{\partial n}{\partial t} = \frac{j}{q \times d} - gN \frac{c}{n_{opt}} - \frac{n}{\tau_{TOT}}$$



## I.2 Population inversion in a semi-conducteur

Condition of Bernard Durratourg

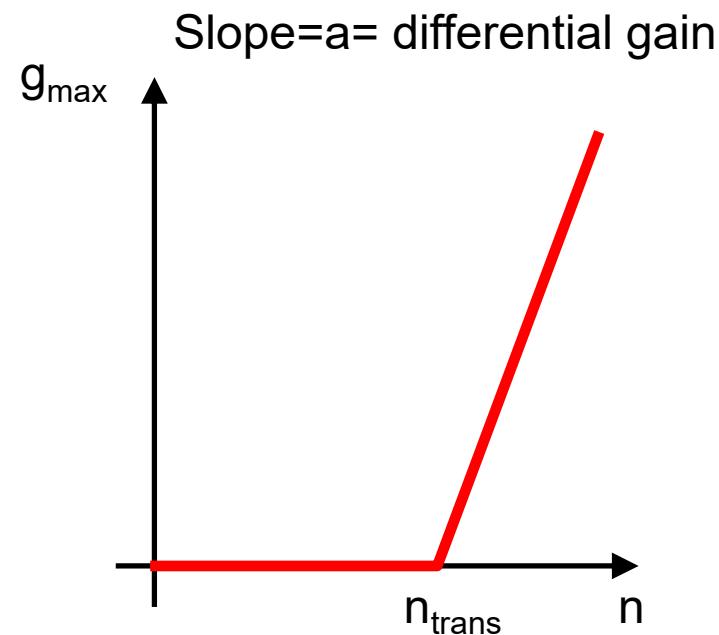
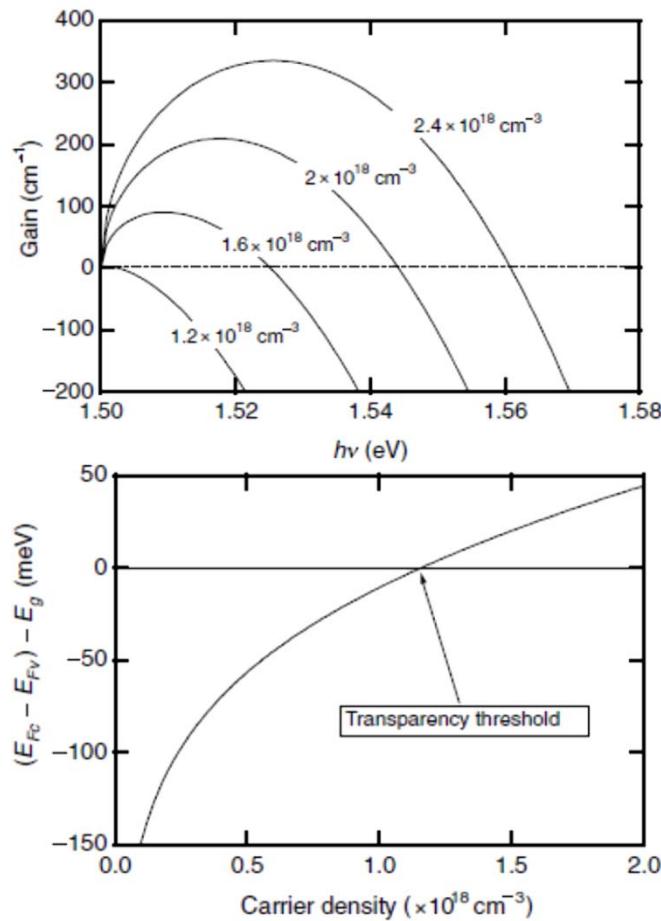
$$E_a < h\nu < E_{fc} - E_{fv}$$



## I.2 Optical gain

Gain calculation: it is proportionnal to the density of states liked to a photon and the occupancy factor for this states (Fermi function with pseudo Fermi levels)

Exemple : GaAs Bulk ( $E_g = 1.424 \text{ eV}$ ) [source E.Rosencher]



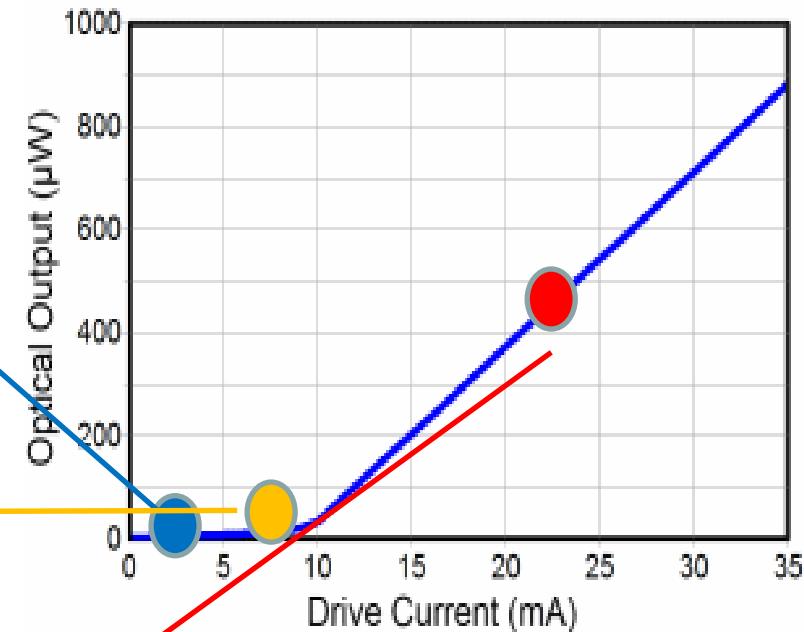
## I.2 Typical feature of electrically pumped semiconductor laser

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– Current is under the transparency =>  
Spontaneous emission only .

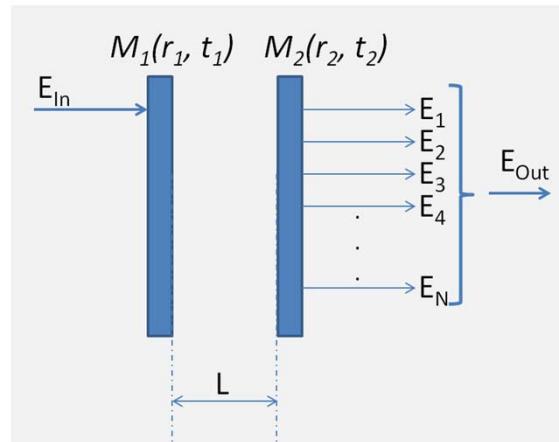
– Current is in between the transparency  
and the laser threshold  
=> Spontaneous emission and stimulated  
emission (gain in not totally recovering the  
losses) no laser emission yet.

– Current is over threshold **Laser operation.**  
**All supplementary carrier (above  $N_{\text{threshold}}$ )**  
recombines and mostly give rise to a  
stimulate emission.

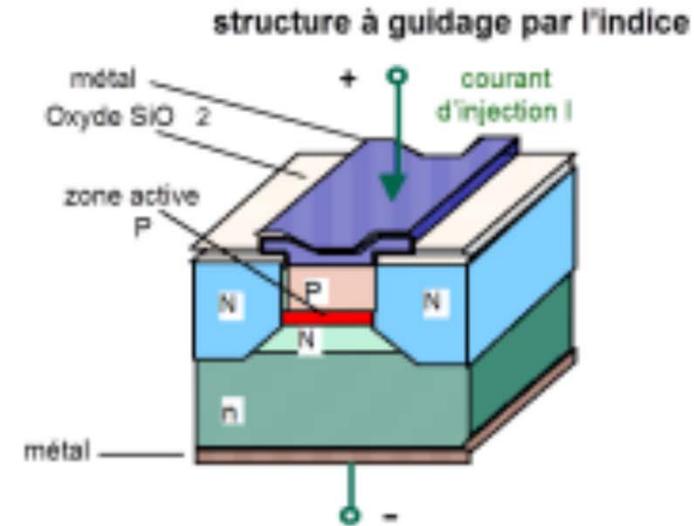


## I.2 Let's summarise

### Fabry-Pérot Cavity



$\Gamma$  = recouvrement du mode avec la région à gain dans la cavité



$$g_{seuil} = \frac{1}{\Gamma} \left( \alpha_p - \frac{1}{2L} \ln(R_1 R_2) \right)$$

$$R_n = \frac{dn}{dt} = -\frac{\delta_n}{\tau_n}$$

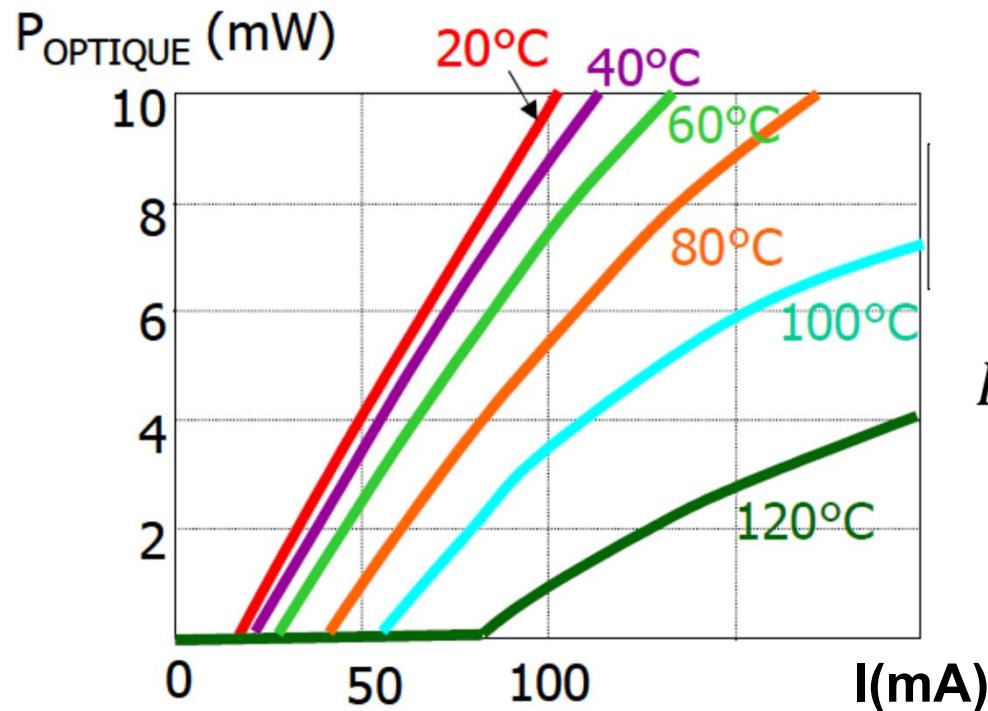
$$\Rightarrow I_{seuil} = qV \frac{n_{seuil}}{\eta_i \tau_{TOT}}$$

$$g \sim a (n - n_{tr})$$

$$I_{seuil} = \frac{qV}{\eta_i \tau_{TOT}} \left( n_{tr} + \frac{g_{seuil}}{a} \right)$$

## I.2 Tempertaure dependance

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$$I_{seuil}(T) = I_{seuil}(T_0) \exp\left(\frac{T_2 - T_1}{T_0}\right)$$

Thermal dissipation and temperature control are key parameters for laser device applications.

## I.2 heterojunction

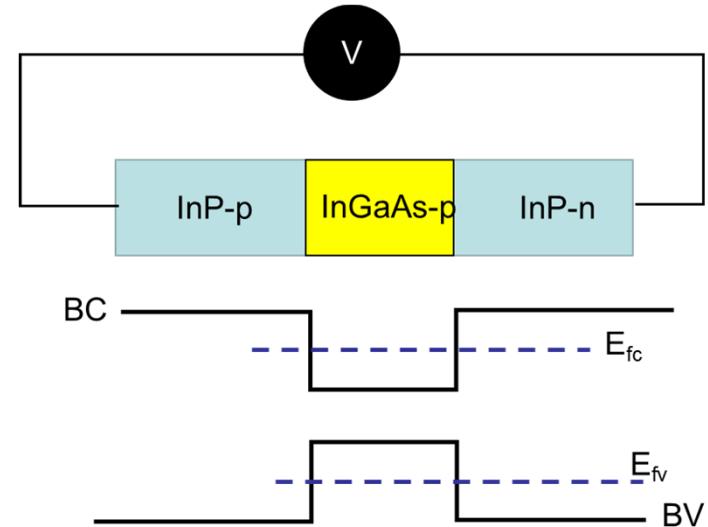
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### homojunction :

- Carrier are injected in width close to the diffusion length of carriers  $\sim \mu\text{m}$

### heterojunction :

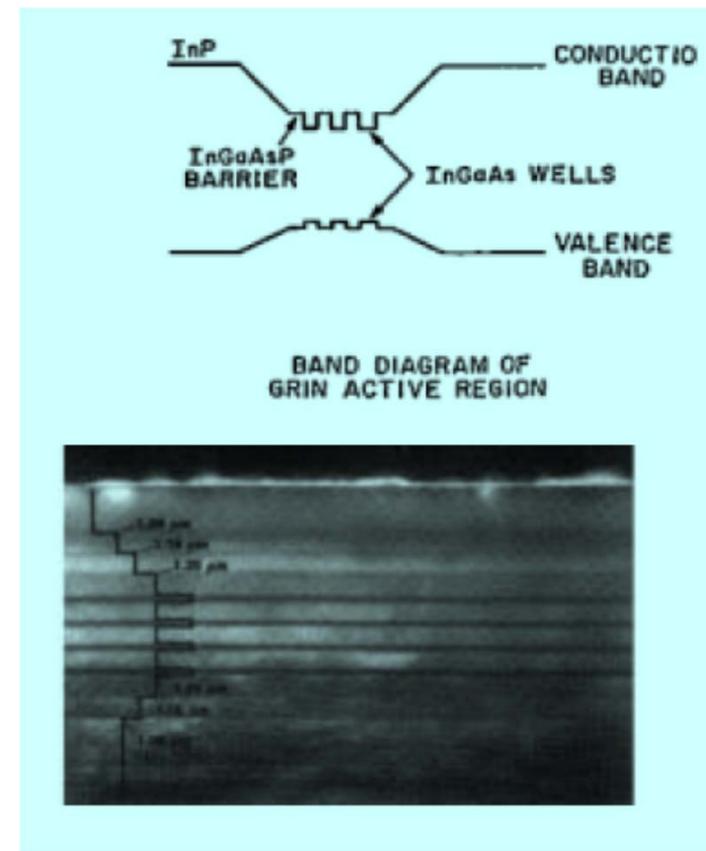
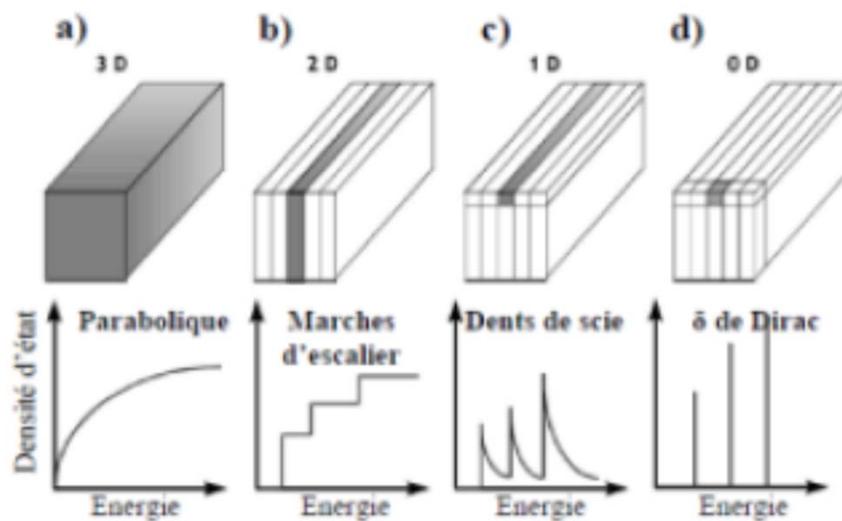
- Electrical confinement.
- Better recovery with optical mode
- Free carrier are injected in a small width (quantum well)
- Multi quantum well active region



## I.2 Multi quantum well active region

- optical recovery with d'un puits unique faible (typiquement ~ 1%)  
=>Utilisation de Multi-puits

- We can also confine in the other dimensions: quantum wires, quantum dots



# I.3 Semiconductor lasers

1962 First GaAs laser diode  
(pulsed operation, cryogenic temperature)  
(General Electric Research Labs)

1970 AlGaAs / GaAs DH laser diode  
(CW, 300K)  
(Ioffe Institute, Bell Labs)

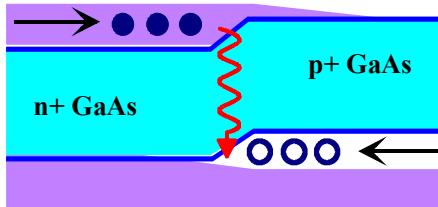
1974 AlGaAs / GaAs DFB laser diode

1976 GaInAsP / InP DH laser diode at 1.2 $\mu$ m  
(CW, 300K)  
(Lincoln Labs)

1977 InGaAsP / InP QW laser  
(Urbana University)

1978 AlGaAs / GaAs QW laser  
(Urbana University)

1979 InGaAsP / InP VCSEL  
(pulsed operation, 77K)  
(Tokyo Institute of Technology)



GaAs homojunction laser diode (1962)

1984 InGaAs / AlGaAs strained QW laser

1988 AlGaAs / GaAs VCSEL  
(CW, 300K)  
(Tokyo Institute of Technology)

1994 InGaAs / AlInAs / InP Quantum Cascade Laser  
(pulsed operation, cryogenic temperatures)  
(Bell Labs)

1995 InGaN/AlGaN/GaN blue laser diode  
(pulsed operation, cryogenic temperatures)  
(Nichia Chemicals)

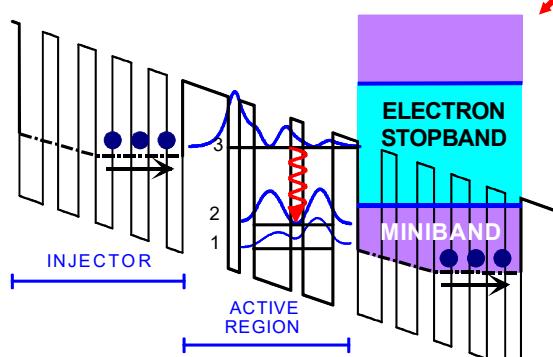
1996 InGaN/AlGaN/GaN blue laser diode  
(CW, 300K)  
(Nichia Chemicals)

1998 AlGaAs / GaAs Quantum Cascade Laser  
(pulsed operation, cryogenic temperatures)  
(Thomson-CSF)

2001 First THz QC laser (SNS, Pisa)

2002 InGaAs / AlInAs / InP Quantum Cascade Laser  
(CW, 300K)  
(University of Neuchâtel)

2005 CW, 300K operation of InGaAs/AlInAs QC lasers at several mid-IR wavelengths (Northwestern University and AGILENT technologies)



Unipolar GaAs/AlGaAs Quantum Cascade Laser (1994)

# I.3 III-V Semiconductor

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
H																	He	
Li	Be																Ne	
Na	Mg																Ar	
K	Ca																Kr	
Rb	Sr																Xe	
Cs	Ba	*															Rn	
Fr	Ra	**															Uuo	
			21	22	23	24	25	26	27	28	29	30	31	32	33	34		
			Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br		
			Sc	Y	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	
			39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	
			Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
			Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	
			71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	
			Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
			70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	
			Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	Uuo	Uuh	Uuh	Uuh	Uuo	
			103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	
			104	105	106	107	108	109	110	111	112	113	114	115	116	117		

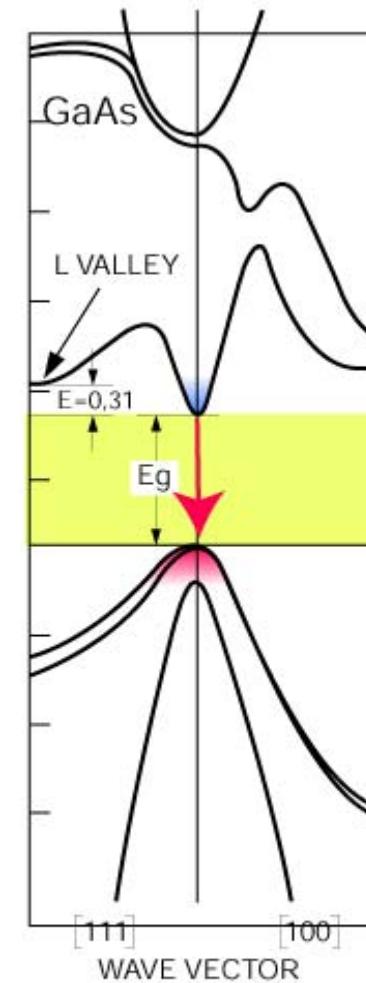
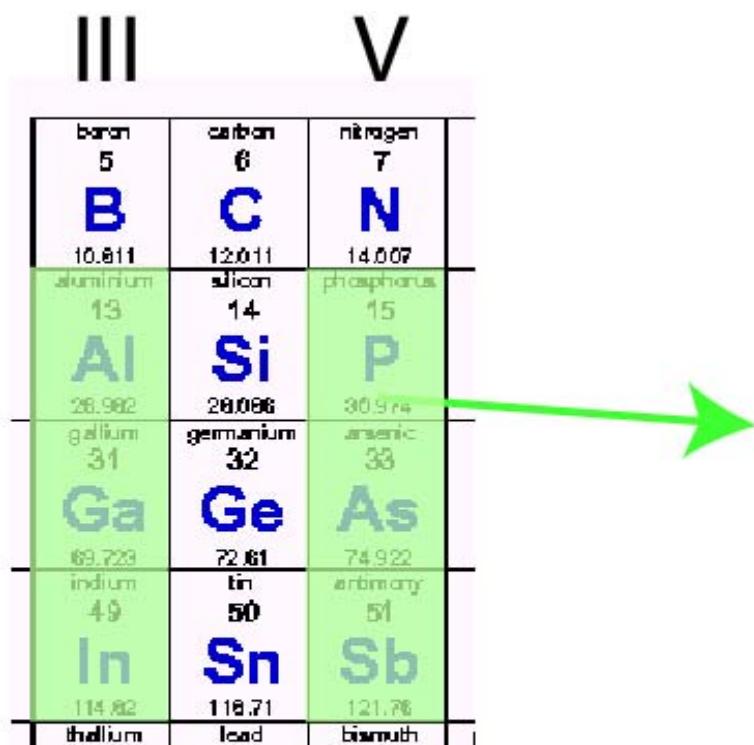
\*lanthanoids

57	58	59	60	61	62	63	64	65	66	67	68	69	70			
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb			

\*\*actinoids

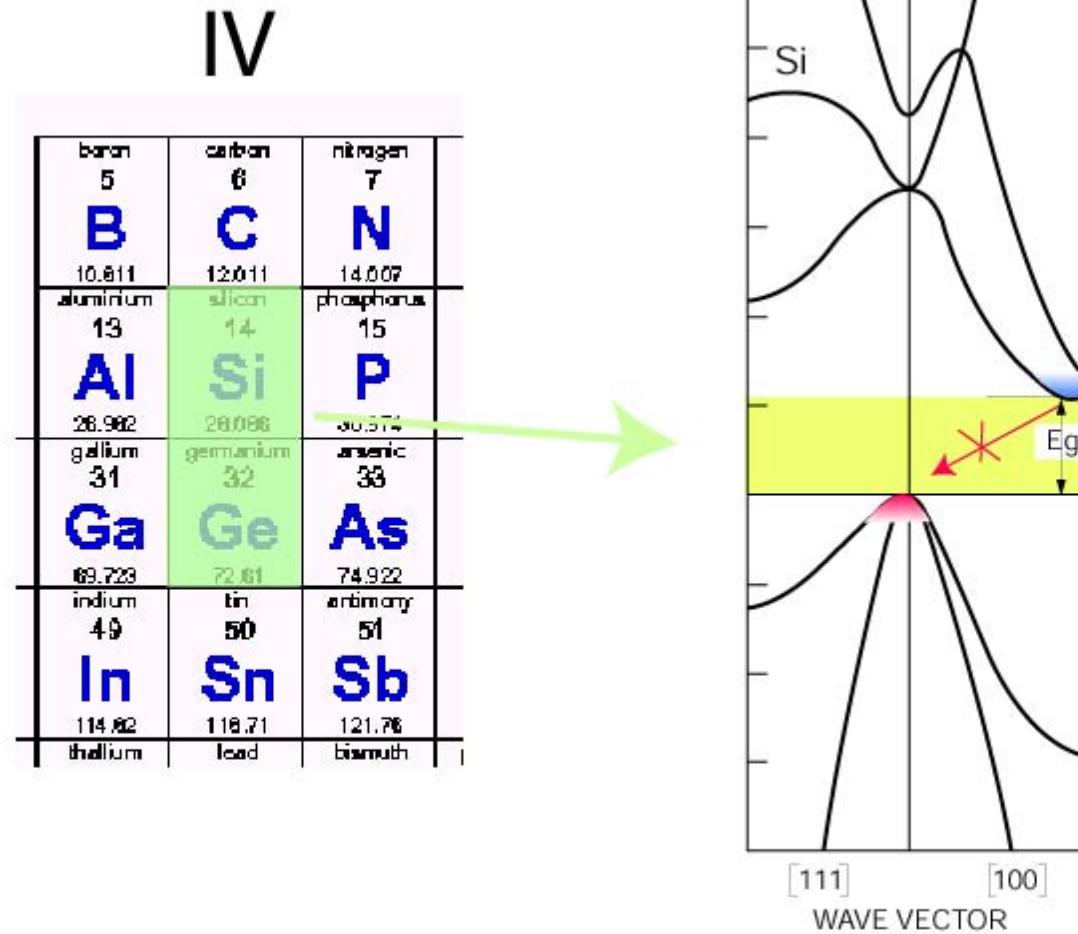
89	90	91	92	93	94	95	96	97	98	99	100	101	102			
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No			

## I.3 Direct gap



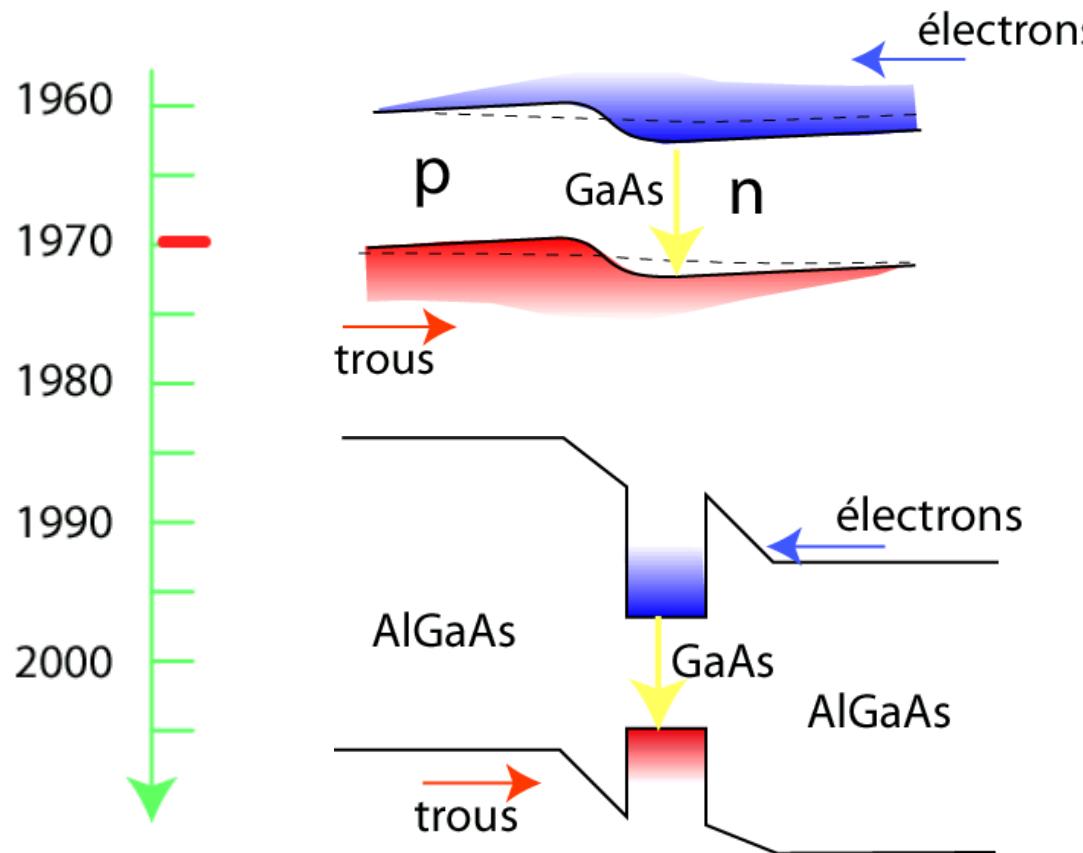
III-V: Emission optique efficace possible

## I.3 Indirect Gap



Pas d'émission optique efficace possible

# I.3 homojunction Vs hetrojunction



## Jonction p-n

- problème de confinement
- guidage de la lumière difficile

**10kA/cm<sup>2</sup> @ 10K**

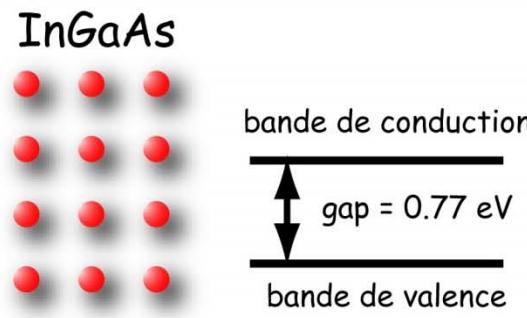
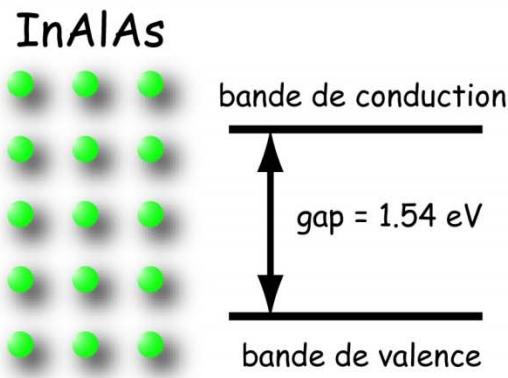
## Hétérojonction

- Confine électrons et trous
- Guidage de la lumière

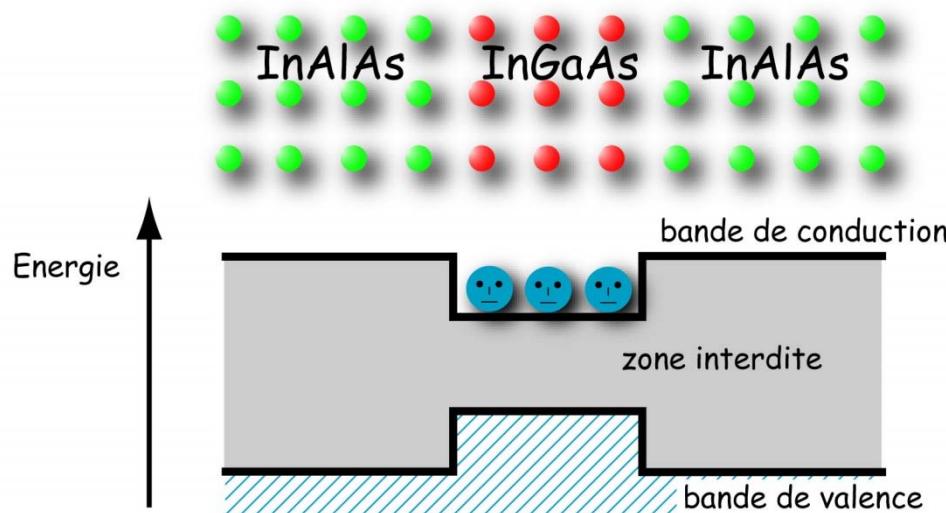
**2kA/cm<sup>2</sup> @ 300K**

Kasaninov (1962)  
Kroemer, Alverov (Nobel)

# Quantum Wells (Dingle 1980)



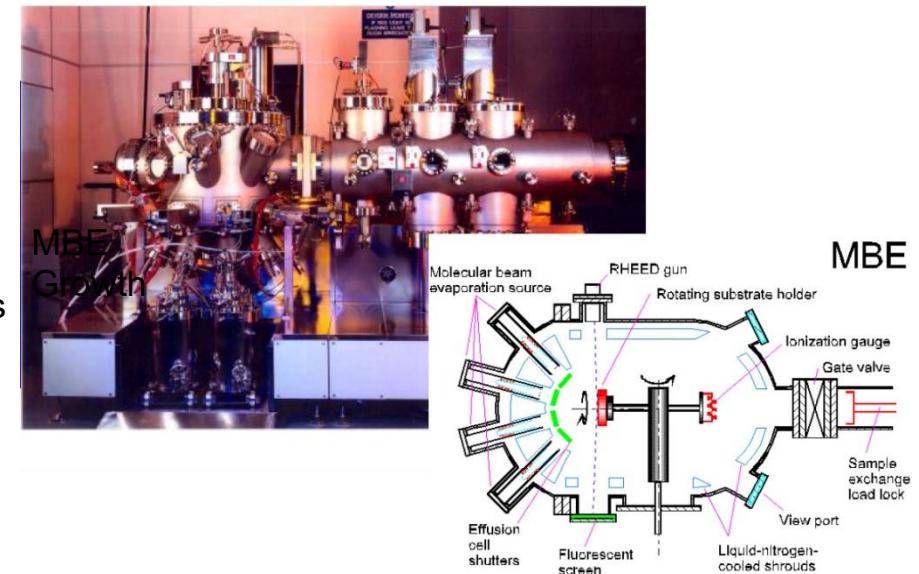
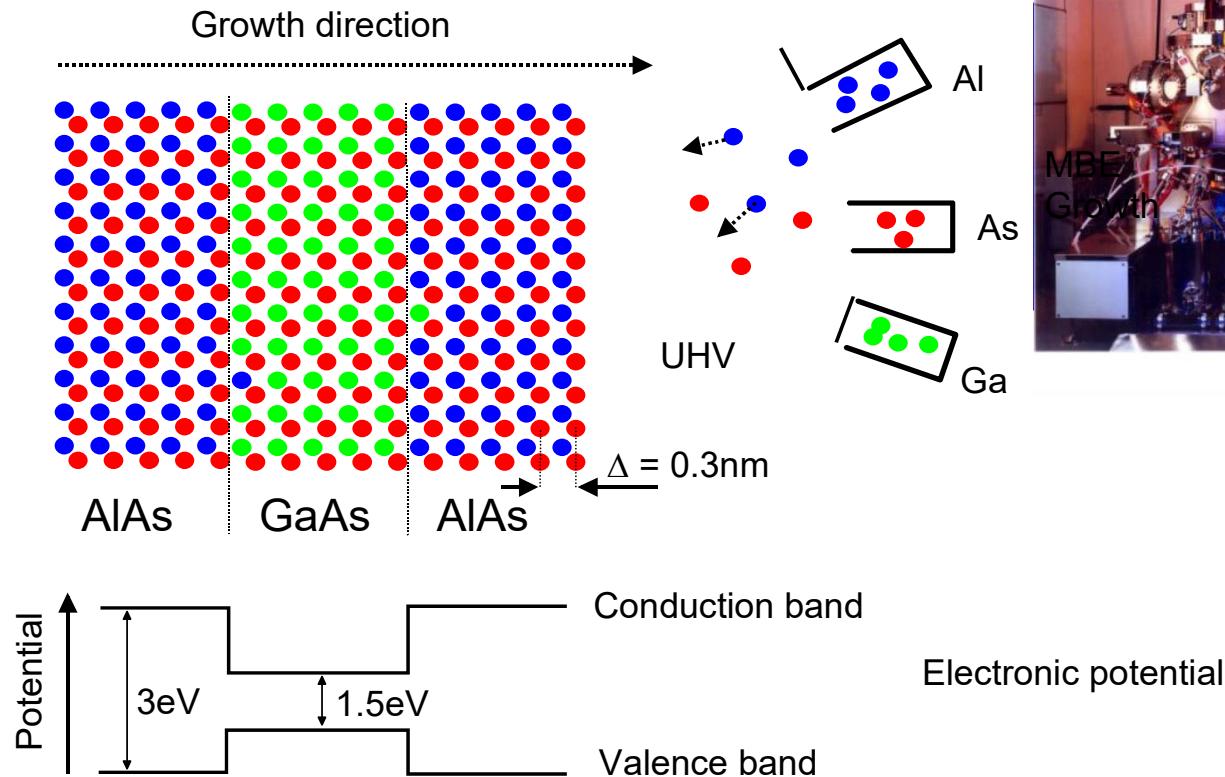
Two semiconductor  
=>two band-gap



heterostructure  
=> Wells and Barriers!!!

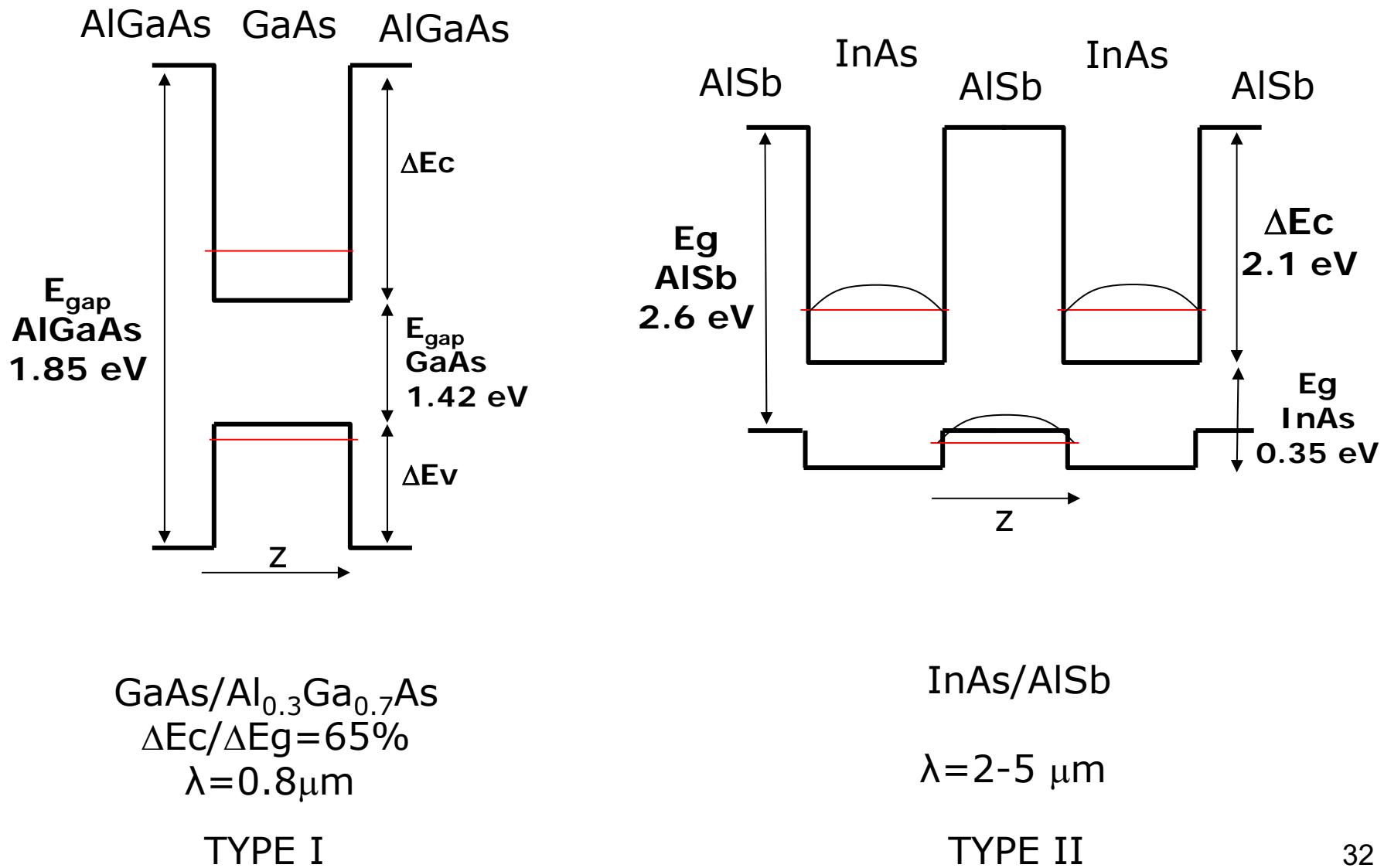
# How heterostructures are fabricated ?

## Molecular Beam Epitaxy MBE



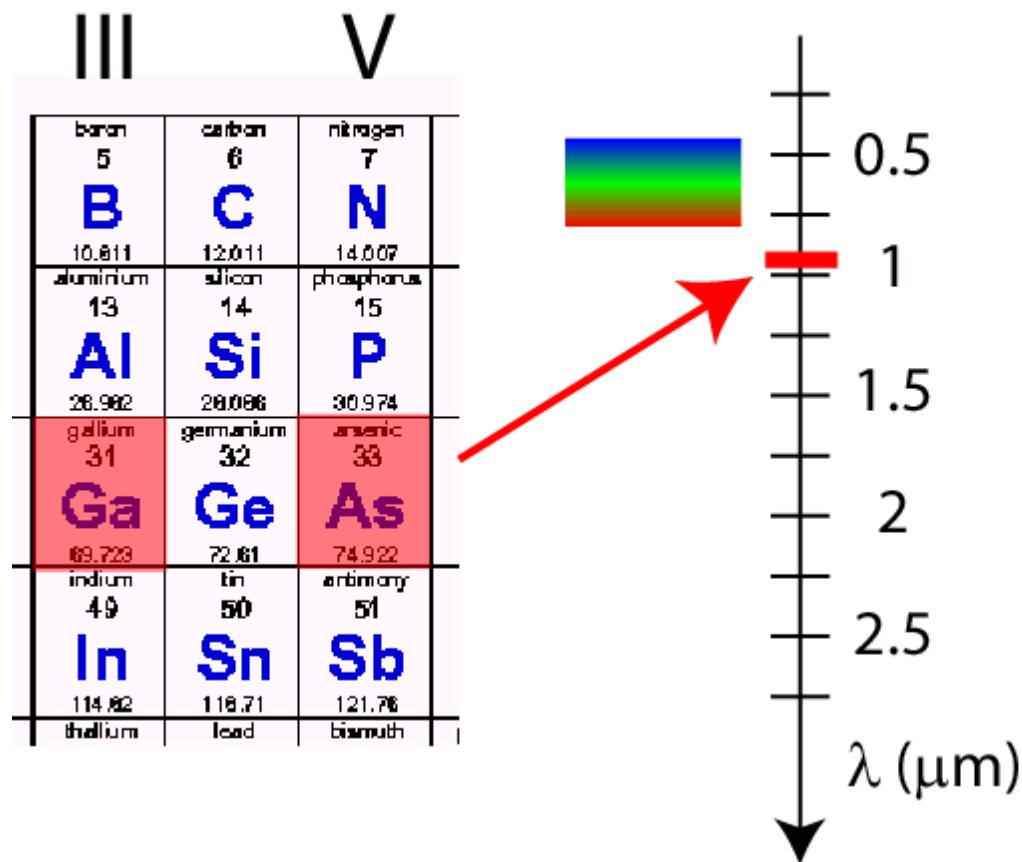
Courtesy: J. Faist

# Quantum wells: type I/II

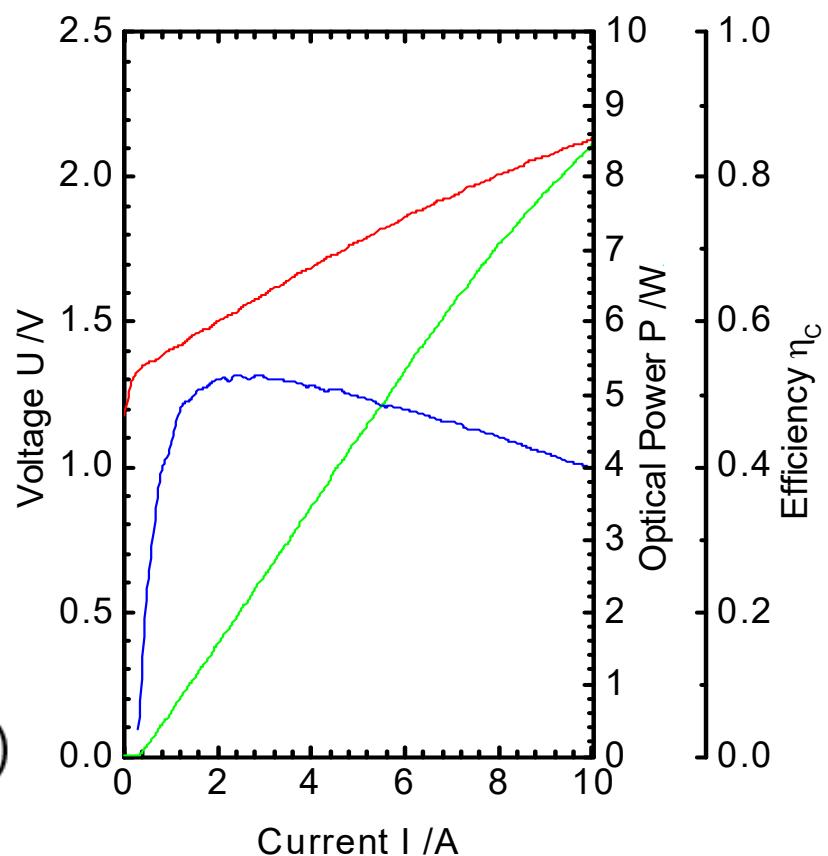


# I.3 Example: GaAs laser diode

Near infrared emission



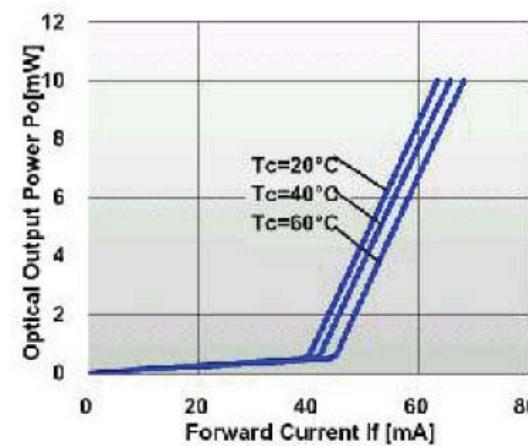
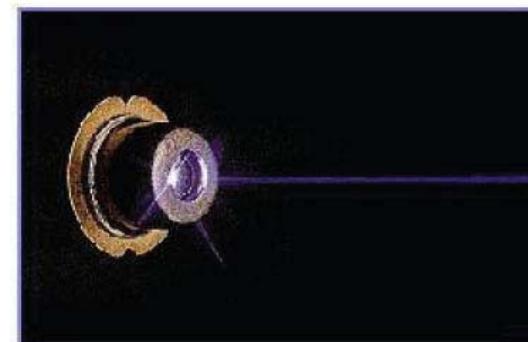
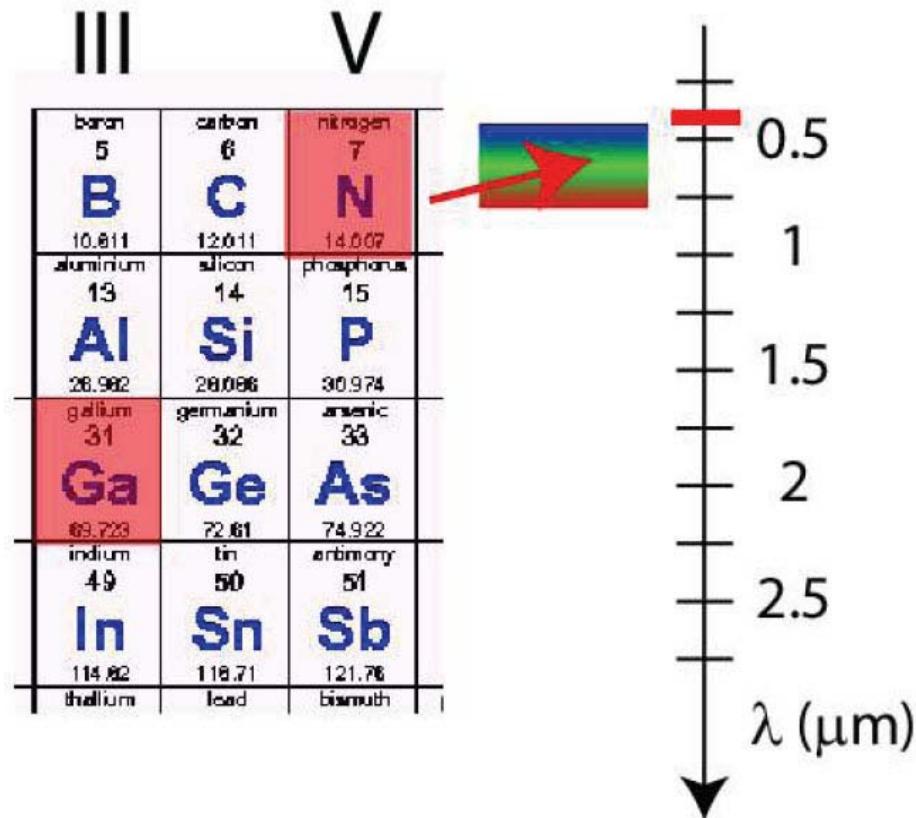
High power laser diodes  
(8.5W) at  $\lambda = 980 \text{ nm}$



Courtesy: THALES

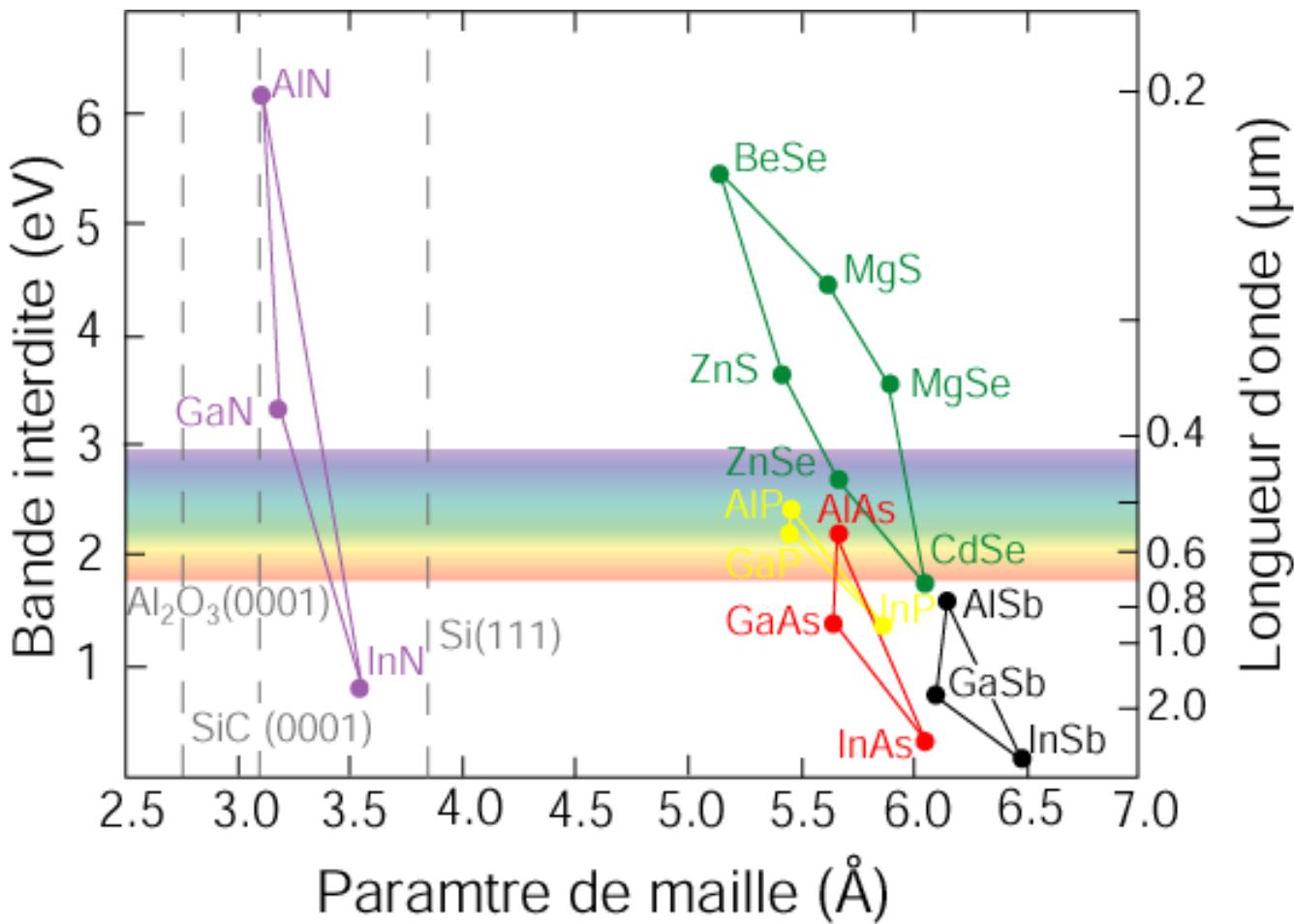
# I.3 Example: InGaN laser diode

Émission dans le bleu



Courtesy: Nichia

## I.3 Lattice matching



Interband transition: to change the color we have to change the material system

# I.4 Some applications

- Le multiplexage en longueur d'onde nécessite de maîtriser la longueur d'onde d'émission
- Laser à émission par la tranche, cavité Fabry- Perot : peut avoir un comportement multimode
- Laser DFB : Distributed Feedback Laser : utilisation d'un réseau de Bragg : rétro-action sélective en longueur d'onde (filtrage spectral)

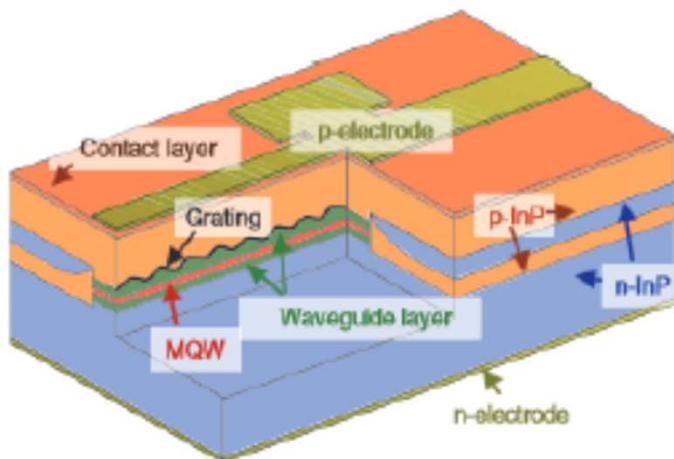


Fig. 2. Schematic structure of a typical DFB laser using InP-based materials.

Source : T. Sato et al, NTT Technical Review

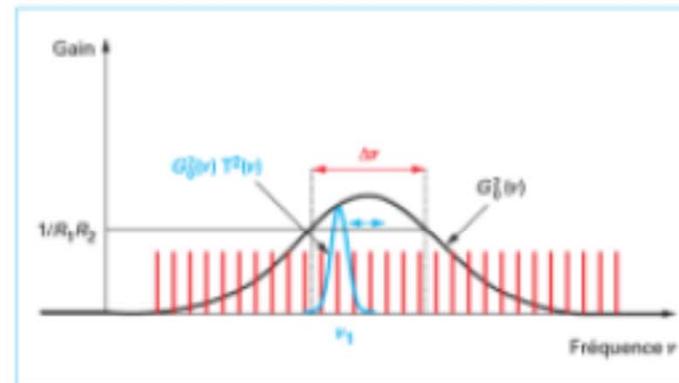
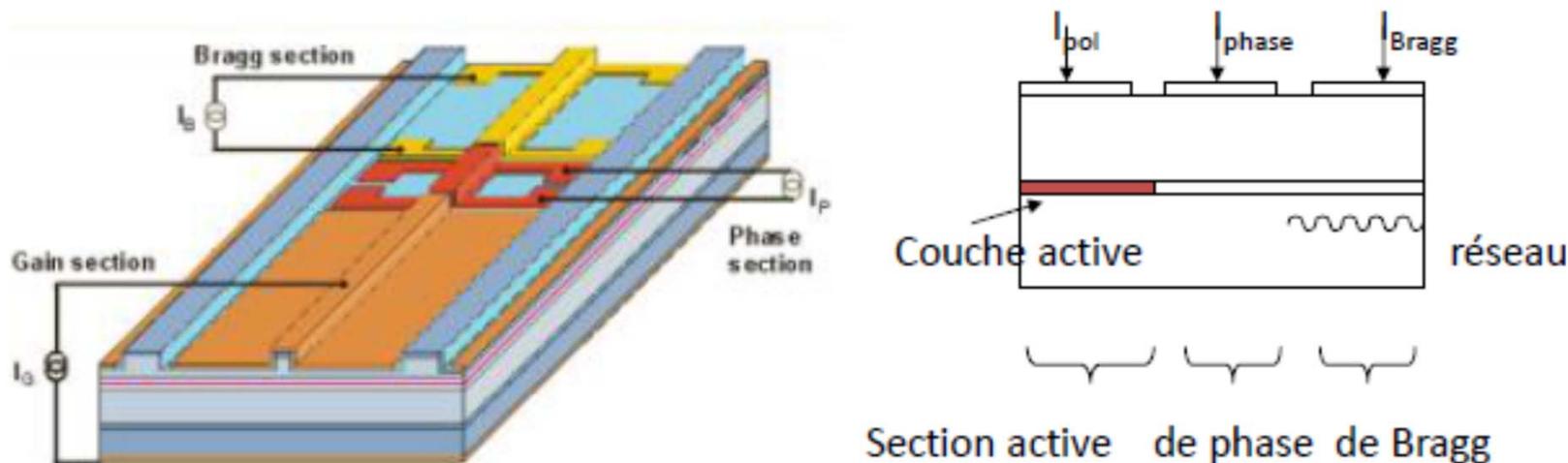


Figure 11 – Condition sur le gain modifiée par un filtre spectral dans la cavité de transmission  $T = 1$  à la fréquence  $\nu_1$ .  
Cas d'une cavité suffisamment grande pour que la condition sur la fréquence soit toujours vérifiée par au moins un mode longitudinal

Source : F. Balembois, technique de l'ingénieur<sup>40</sup>

## I.4 WDM (wavelegth direct multiplexing)

- Accordabilité de la longueur d'onde d'émission :
- Laser DBR (Distributed Bragg reflector) : accordabilité de la fonction de filtrage

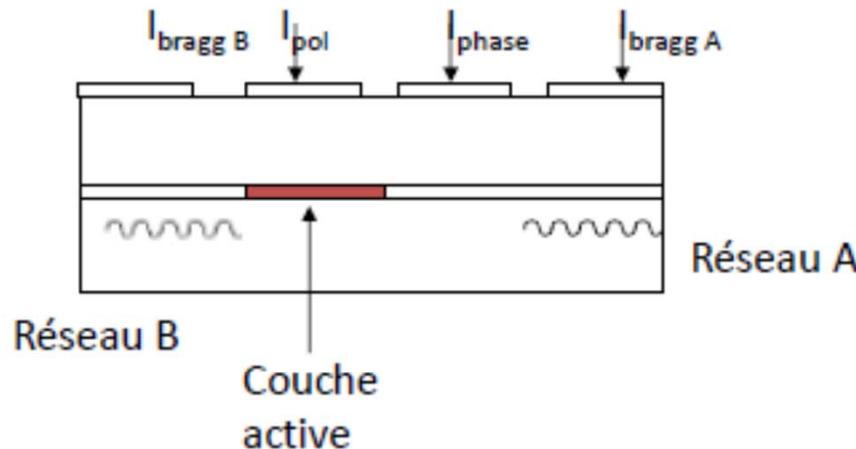


Variation d'indice par injection de porteurs dans les régions de Bragg et de phase

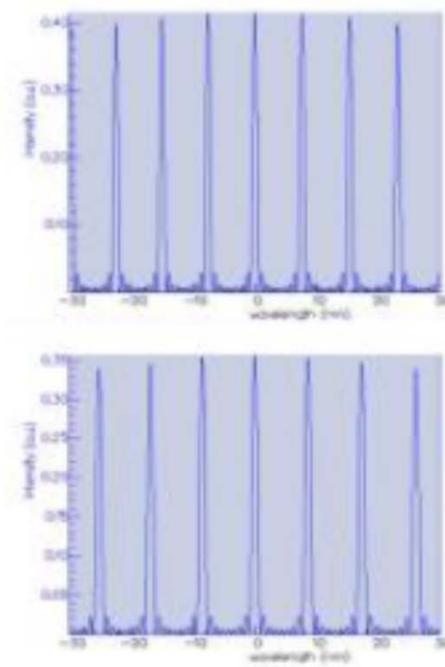
Accordabilité par saut (section de Bragg)  
Et accordabilité continue (section de phase)

## I.4 WDM (wavelegth direct multiplexing)

- Laser DBR : accordabilité typique  $\sim$  dizaine de nanomètres
- SG-DBR (Sampled Grating- Distributed Bragg reflector)  
pour une accordabilité sur une plus grande plage de longueur d'onde



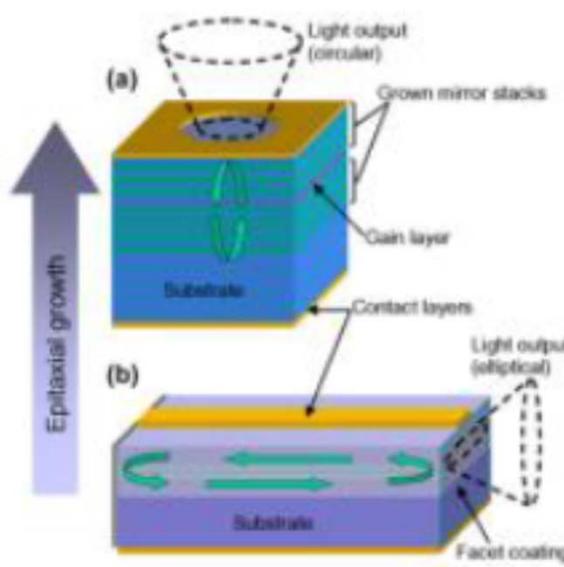
Effet Vernier entre les peignes des 2 miroirs de Bragg  
Accordabilité continue sur plus de 40 nm



Reflection spectra of sampled gratings A and B.  
Both consist of a comb of reflections, but the mode (reflection) spacings differ because the sampled gratings have different burst periods.

## I.4 VCSELs

- Diode laser à cavité verticale émettant par la surface  
(VCSEL *vertical-cavity surface-emitting laser*)



Mise en œuvre une cavité F.P. très courte ( $\approx \mu\text{m}$ ) par épitaxie et miroirs de Bragg à couches diélectriques → émission monofréquence.

### Avantages :

- intervalle spectral libre énorme  $\Rightarrow$  émission monomode
- fabrication collective sur un substrat (technologie planaire, possibilité d'un unique étape d'épitaxie)
- test des composants avant la découpe du substrat
- matrices de VCSELs possible  $\Rightarrow$  interconnexions optiques massivement parallèles

## I.4 III-V On Silicon

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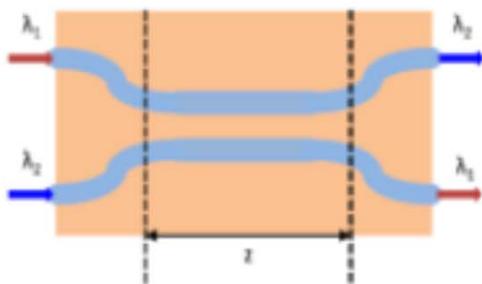
- Matériaux III-V : possibilité d'avoir du gain optique (bon rendement quantique interne)
- Photonique silicium : bonnes propriétés de guidage optique (fort contraste d'indice=> dispositifs compacts)=> plus de flexibilité dans la conception des parties optiques



### Intégration de lasers hybrides III-V sur silicium

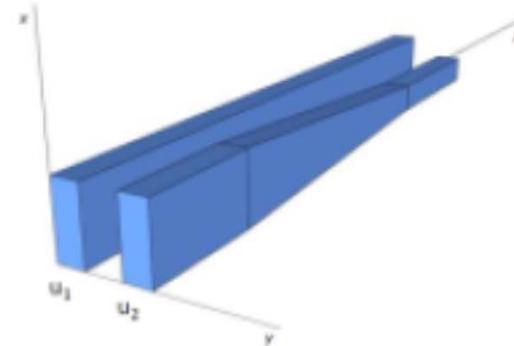
- Lasers DFB ou DBR intégrés sur silicium
- Nouvelles possibilités : utilisation de résonateurs en anneaux pour le filtrage spectral  
(objectifs : diminution du courant de seuil, bonne accordabilité, bonne suppression des modes secondaires....)

## I.4 III-V On Silicon

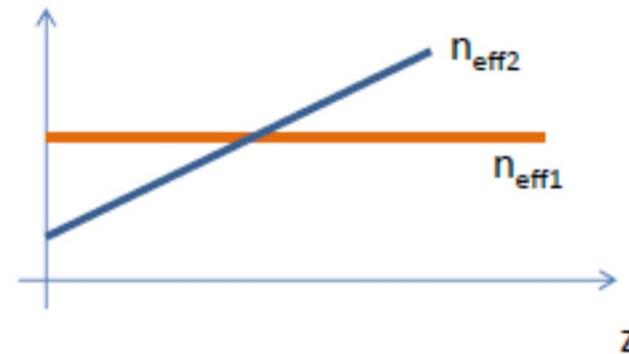


Coupleur directionnel v.s.

- *Oscillation de la lumière entre les 2 guides*
- *Couplage 100 % si les guides sont identiques*



Coupleur avec variation le long du guide  
(tapered coupleur)



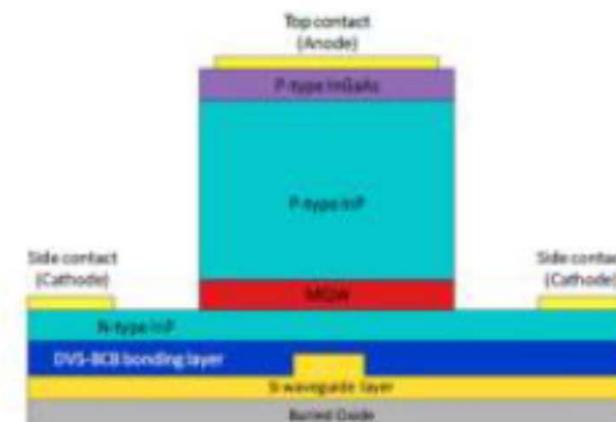
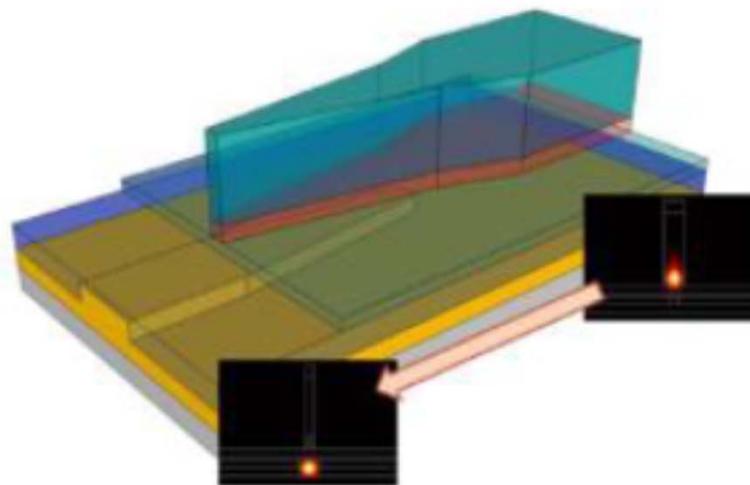
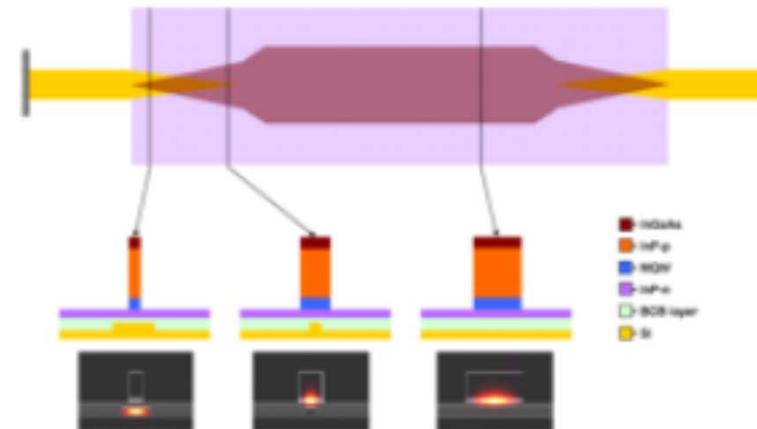
*Possibilité d'avoir un transfert total de l'énergie*

Source : PhD M. Lamponi

# I.4 III-V On Silicon

## Couplage III-V / guide SOI

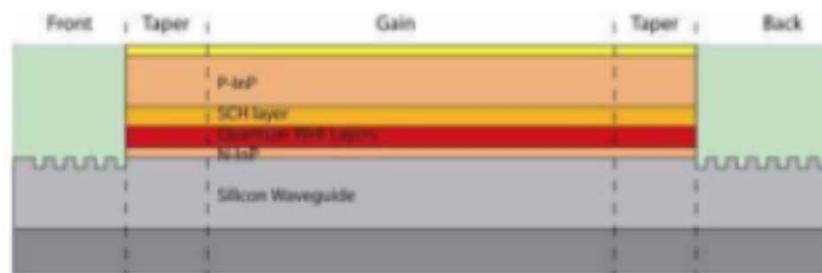
Variation du guide le long du coupleur



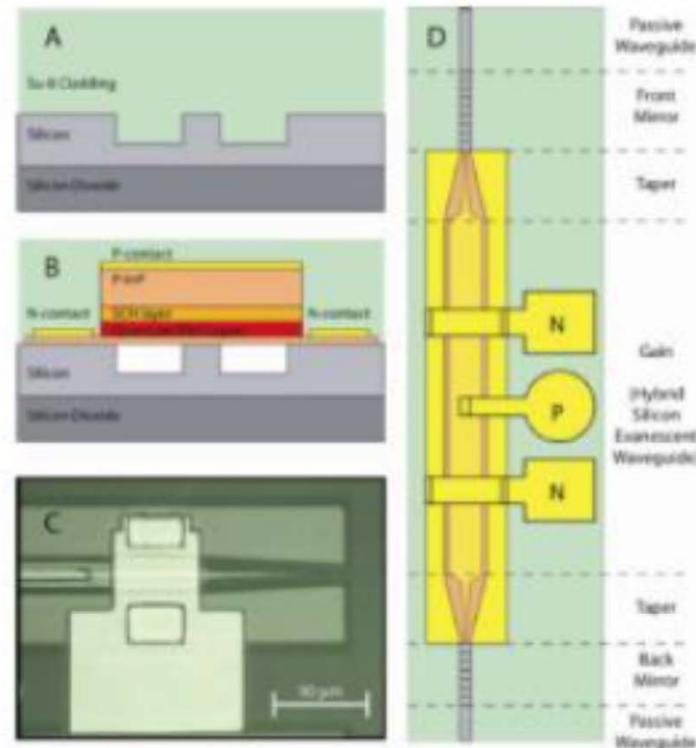
Source : PhD M. Lamponi

# I.4 III-V On Silicon

## Laser DBR hybride III-V sur silicium



Couplage de la lumière du guide d'onde SOI vers la région active III-V => couplage adiabatique (accord de phase)

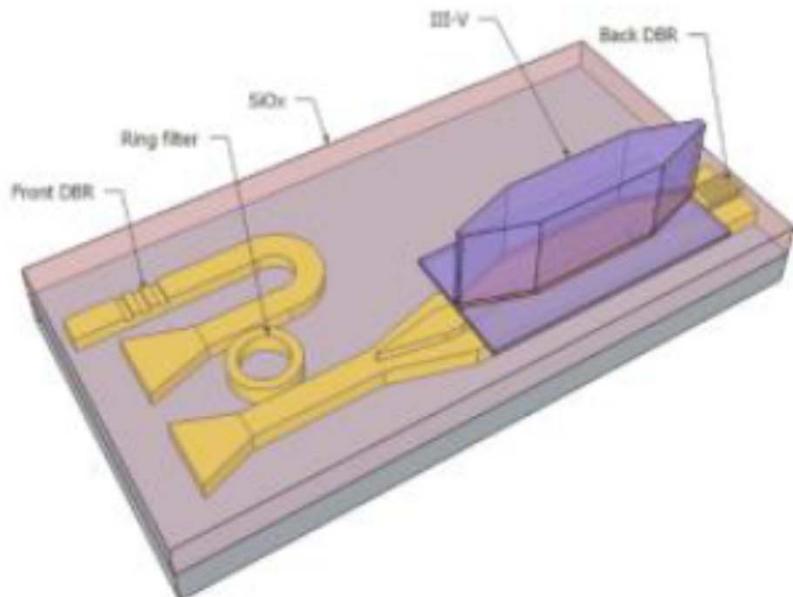


Source : A. fang et al

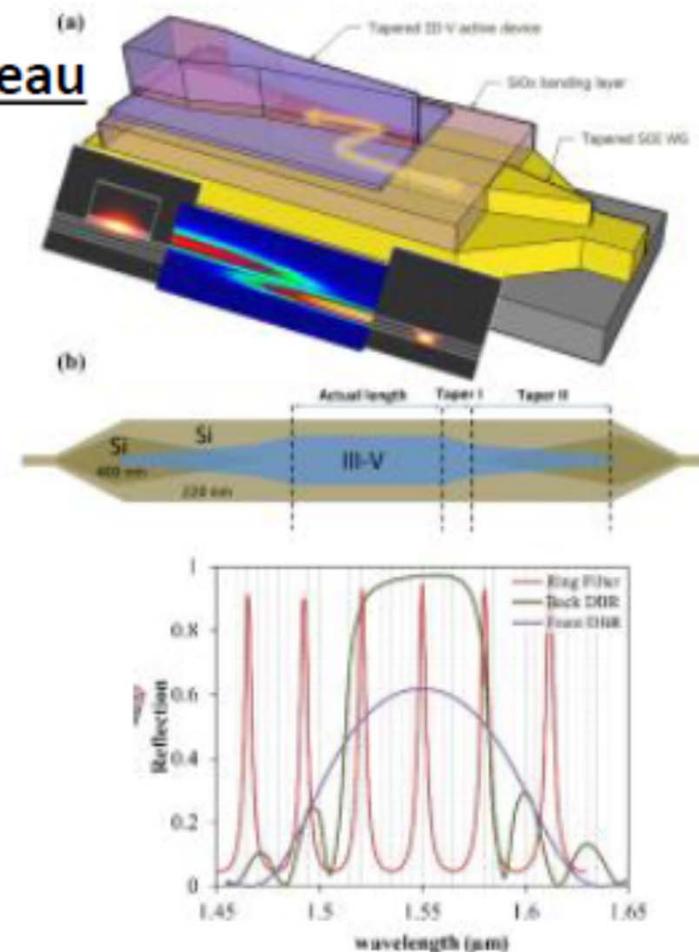
# I.4 Laser III-V intégré sur Silicium

## Laser hybride III-V sur silicium accordable par résonateur en anneau

*Keyvaninia et al, Optics express 2013*



Accordabilité du laser par chauffage  
du résonateur en anneau : variation  
d'indice de réfraction par la température



Calcul des spectres des réseaux et du filtre

## I.4 III-V On Silicon

### Laser hybride III-V sur silicium accordable par résonateur en anneau

Source Keyvaninia et al, Optics express 2013

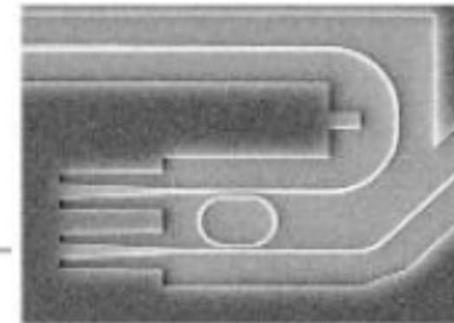
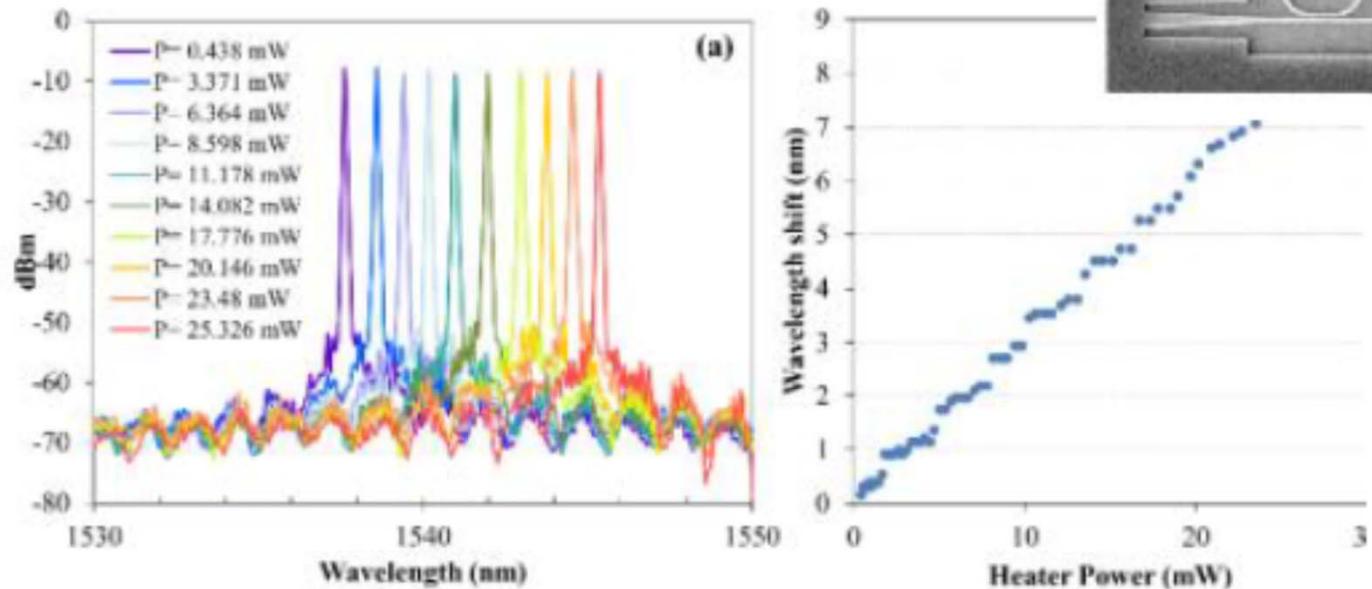
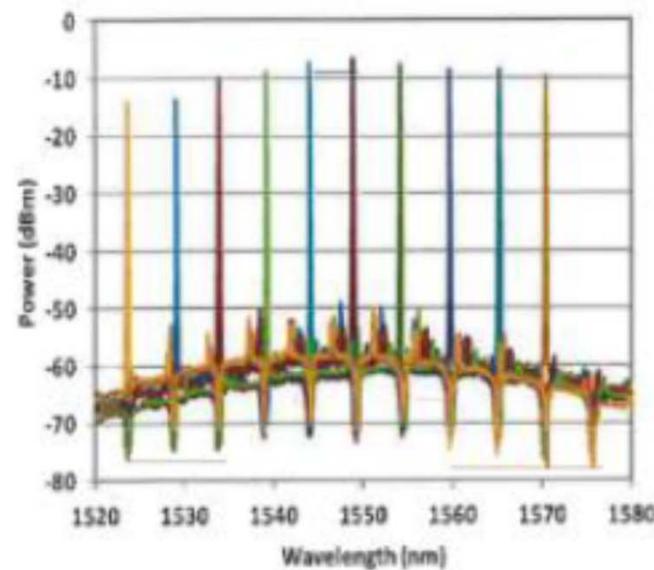
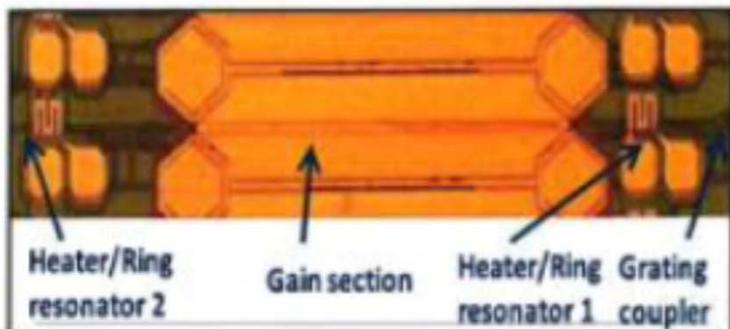
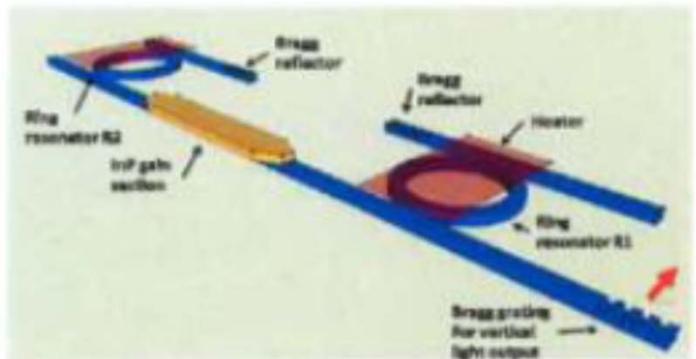


Fig. 8. (a) Super-imposed laser spectra for several values of the heating power (b) laser wavelength as a function of the power dissipated in the heater, at 20°C and a laser injection current of 80 mA.

## I.4 III-V On Silicon

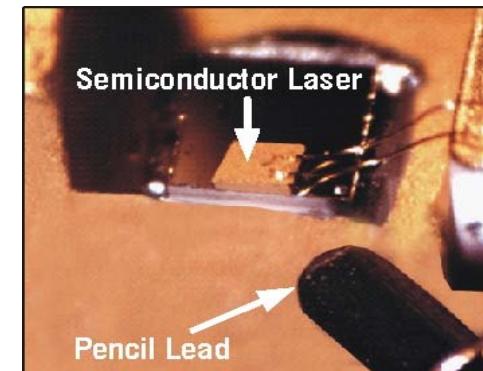
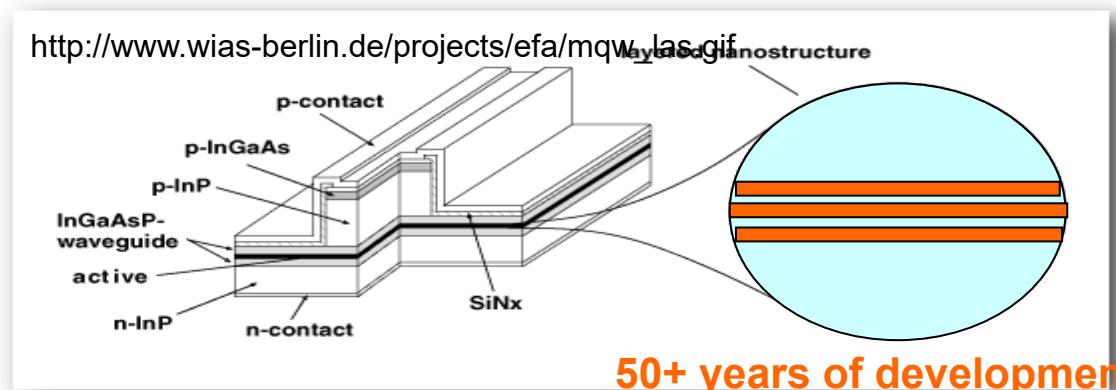
- Pour une plus grande accordabilité : utilisant de 2 résonateurs en anneau différents (effet Vernier)



Source : G.H Duan

# I.5 Now days: diode lasers are everywhere!

- Semiconductor lasers
  - Laser pointer (red, green); scanner (red, infrared); medicine (VIS, IR)
  - CD player (IR); Optical disk (red); high density data storage (blue);
  - Light-wave communication sources (long distance telecommunication ... internet, IR)



<http://repairfaq.ece.drexel.edu/sam/CORD/leot/module3/pencil.jpg>

- But still exciting research to achieve :
  - Non-linear photonics
  - Short pulse high energy generation
  - Frequency combs

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## I. Diode lasers

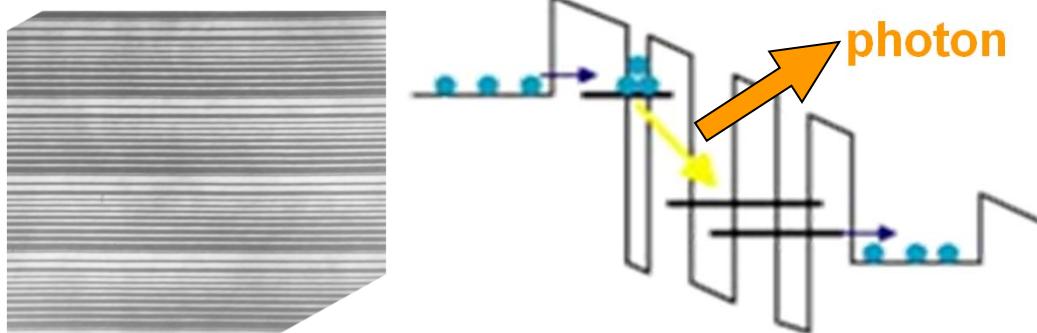
- I.1 light-matter interaction: Optical transition in semiconductors
- I.2 Semiconductor lasers (Inter-band transition ): bulk SC, Quantum wells.
- I.3 III-V semiconductors, wavelength selection,
- I.4 Diode laser applications: wavelength multiplexing, III-V on Silicon...

## II. Quantum cascade lasers

- II.1 Introduction: Mid Infrared photonics, motivations.
- II.2 Associated technologies: Growth, fabrication.
- II.3 State of the art
- II.4 Quantum cascade laser: Laser waveguide, active region, mode control
- II.5 Laser characterization
- II.6 QCL in research: QCL as Surface plasmon polariton source

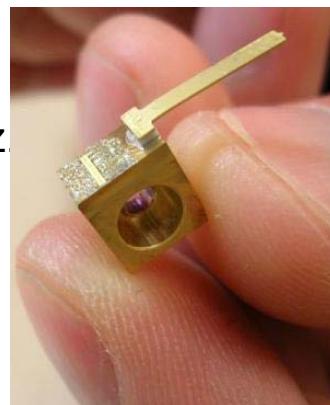
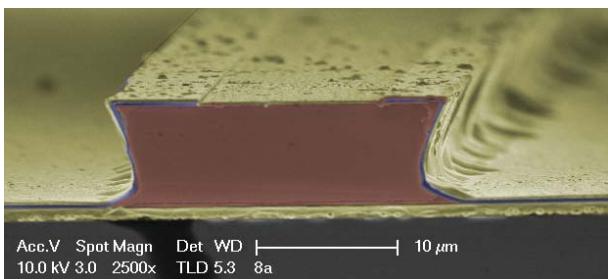
## II.1 Mid Infrared photonics

**Inter-sub-band photonics:** Photons are emitted and/or absorbed in inter-sub-band transition (unipolar devices operating in the conduction band).

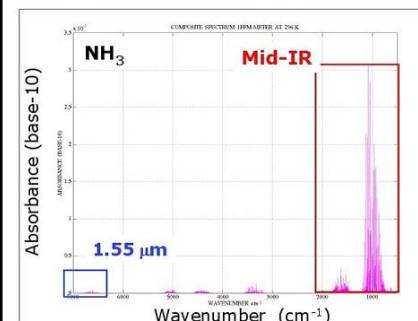


**Emission:** Quantum cascade laser  
QCL

- Compact semiconductor sources operating the Mid-IR and in the THz



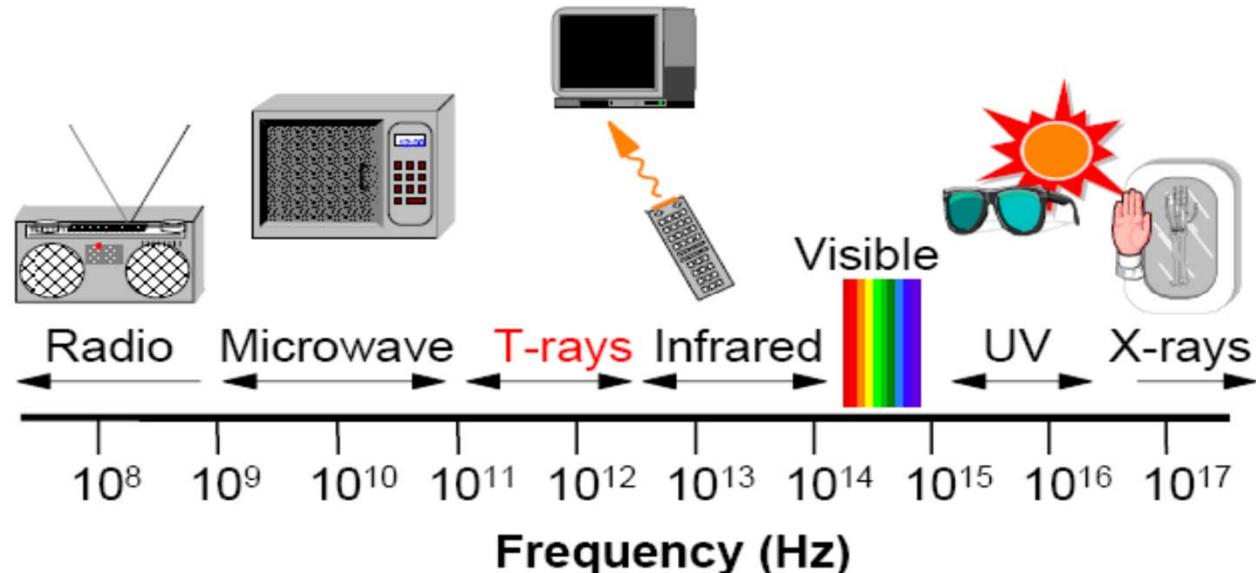
**Détection:** Quantum cascade detector (QCD), Quantum Well Infrared Photodetector (QWIP)



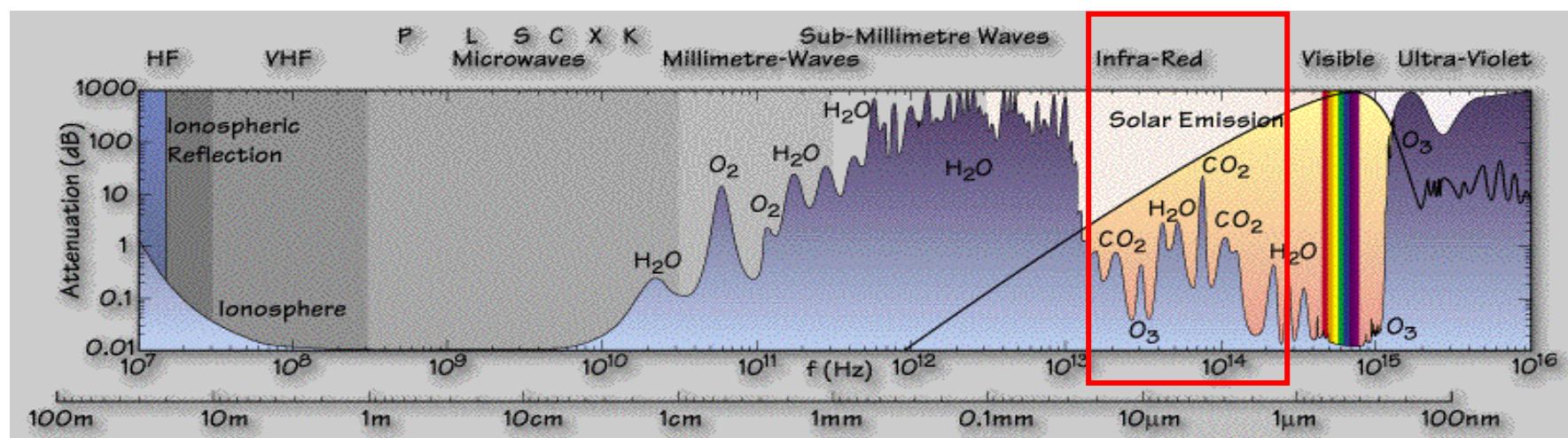
- Mid-IR (3μm-20μm): detection and spectroscopy for environment, Health and Security

## II.1 Mid Infrared: Where is it?

Mid IR:  
10 → 100 THz  
 $30\mu\text{m} \rightarrow 3\mu\text{m}$

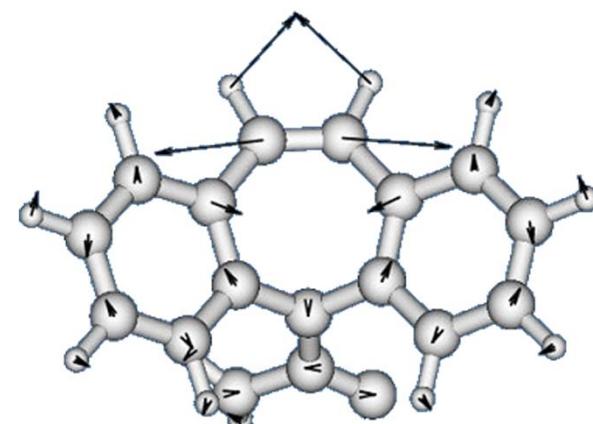
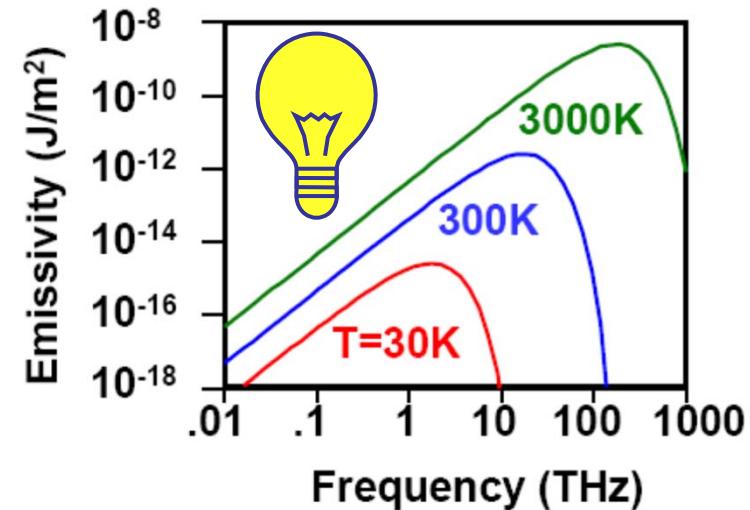


□  $\nu=40 \text{ THz}, \lambda=7.5\mu\text{m}, \sigma=1330 \text{ cm}^{-1}, h\nu=160 \text{ meV},$

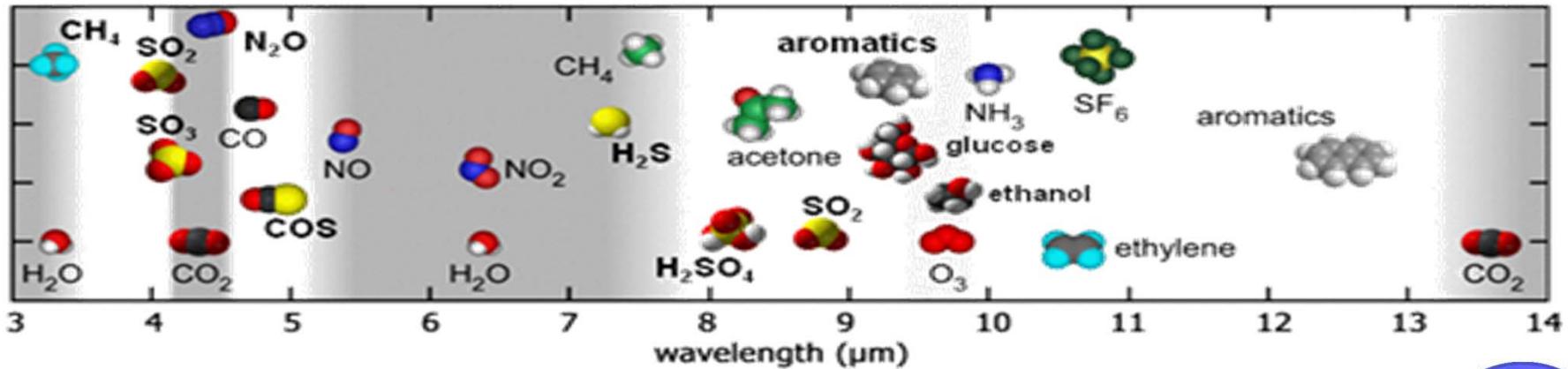


## II.1 Application domains

- Black body is natural Mid IR source. All heat sources are potential objects to detect.
- Major chemical species have an intense spectral absorption in the Mid-IR (compared to short wavelengths): Intra molecular absorption
  - Spectroscopy
  - Detection
  - Imaging
  - Defense/security
  - Free space communications

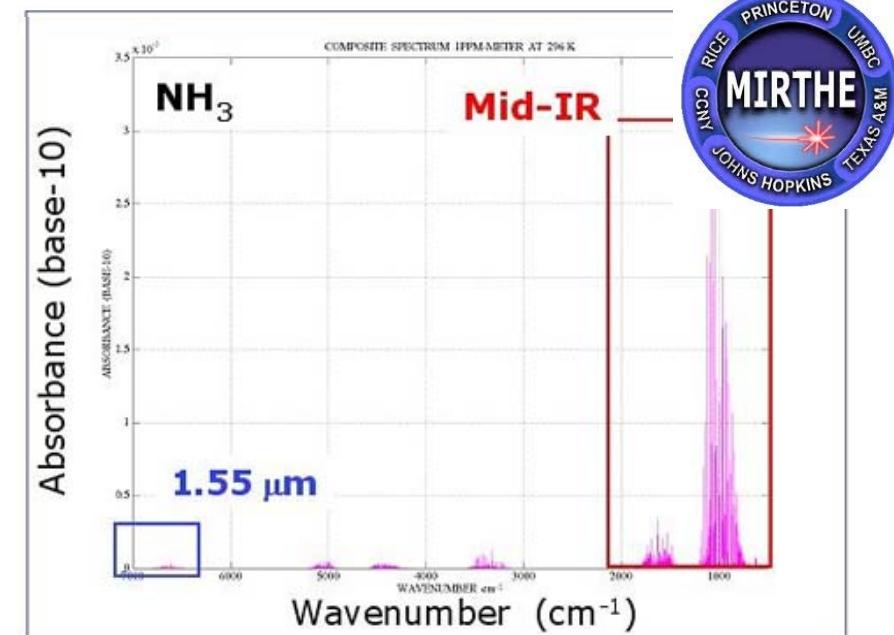


## II.1 Applications: Spectroscopy

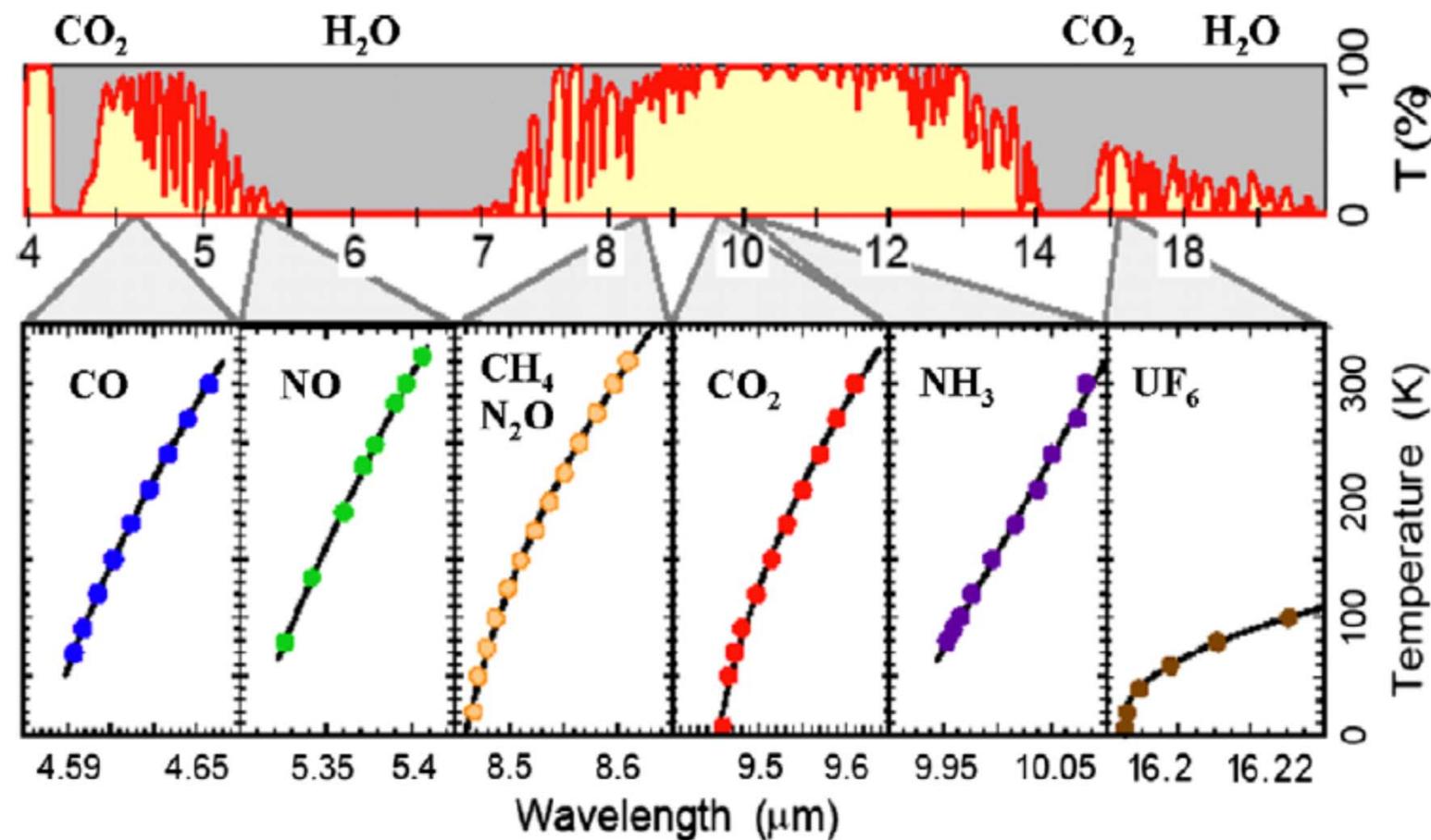


### Infrared Spectral Region

- Intramolecular bond vibrations
- Indirectly affected by crystal changes
- Intense spectral absorption in the Mid-IR => Single molecule detection.



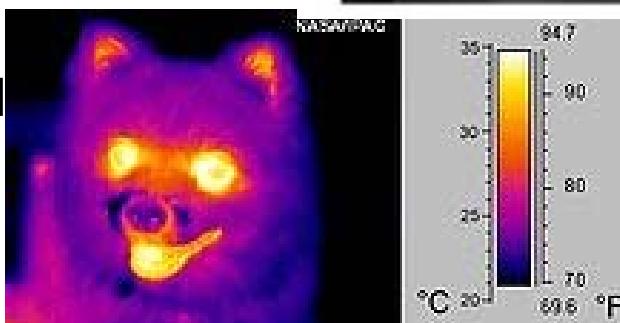
## II.1 Applications: Gaz detection



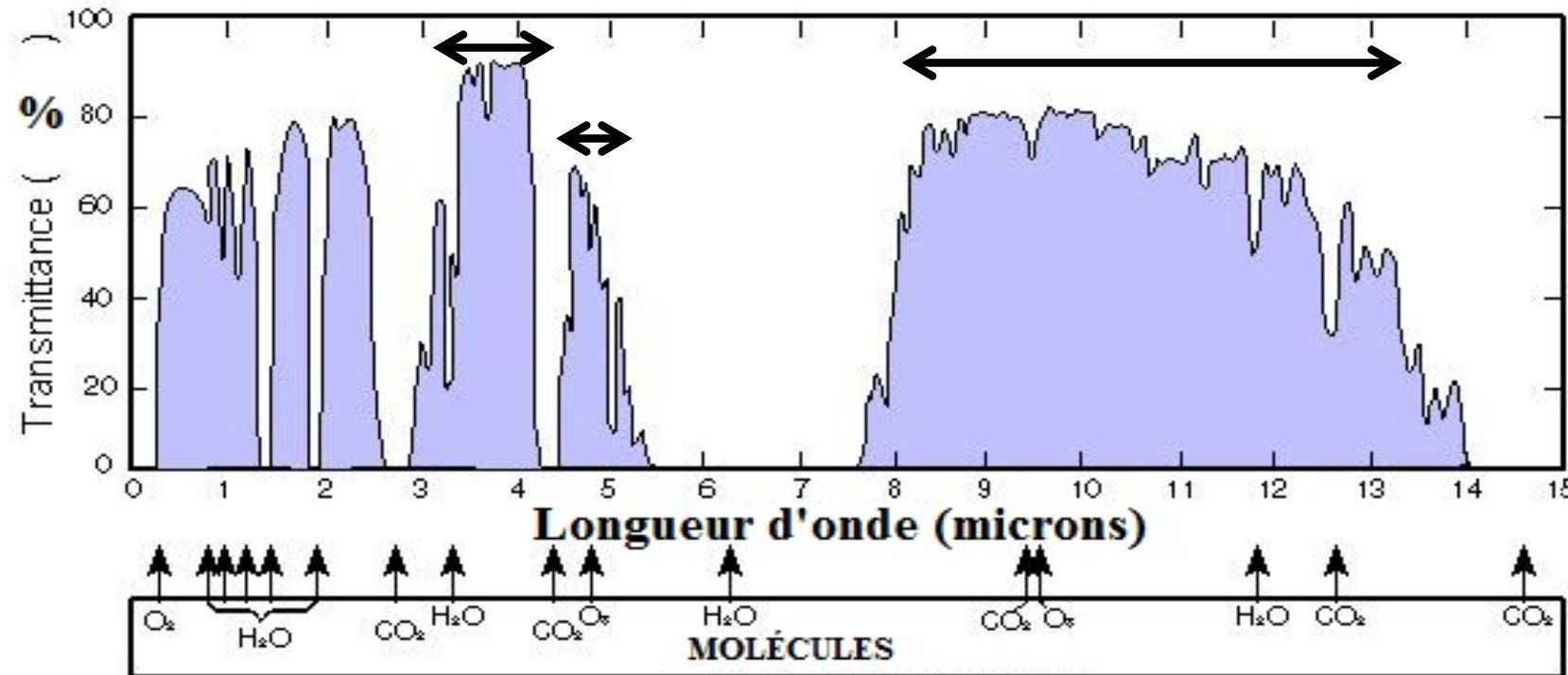
R.F. Curl et al. Chem. Phys. Lett. 487 (2010) 1–18

## II.1 Applications: Imaging

- Night imaging:
  - **Passive:** An infrared detector can detect the hottest objects, when the number of visible photons is reduced (night).
  - **Active:** An infrared spotlight can illuminate a scene, the reflected infrared photons can then be used for imaging.
- Thermal imaging/thermography
  - Measure and sense temperature distant objects.
- Earth/Space imaging



## II.1 Applications: Free space Communication



- **Free space communications:** There are few spectral windows where the atmosphere is transparent  
"Atmospheric widows"

## II.1 Applications: Guiding/counter measure

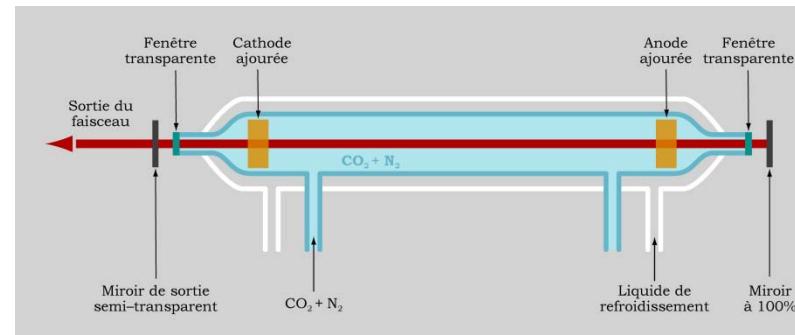
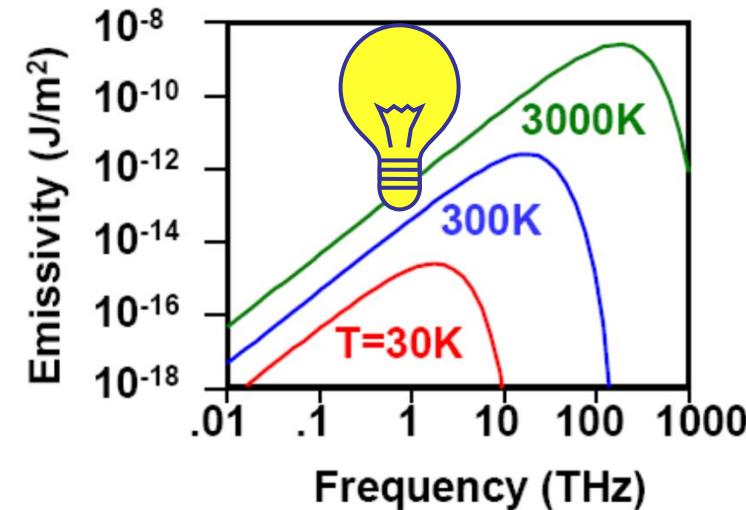
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- Military applications:
  - Guiding: Thermal detection (Passive or active) is applied to guide rockets to their targets (heat source).
  - Counter measure: An intense mid-IR source (a laser) can blind or lure a missile or a rocket. Useful for plane protection (air force one!)



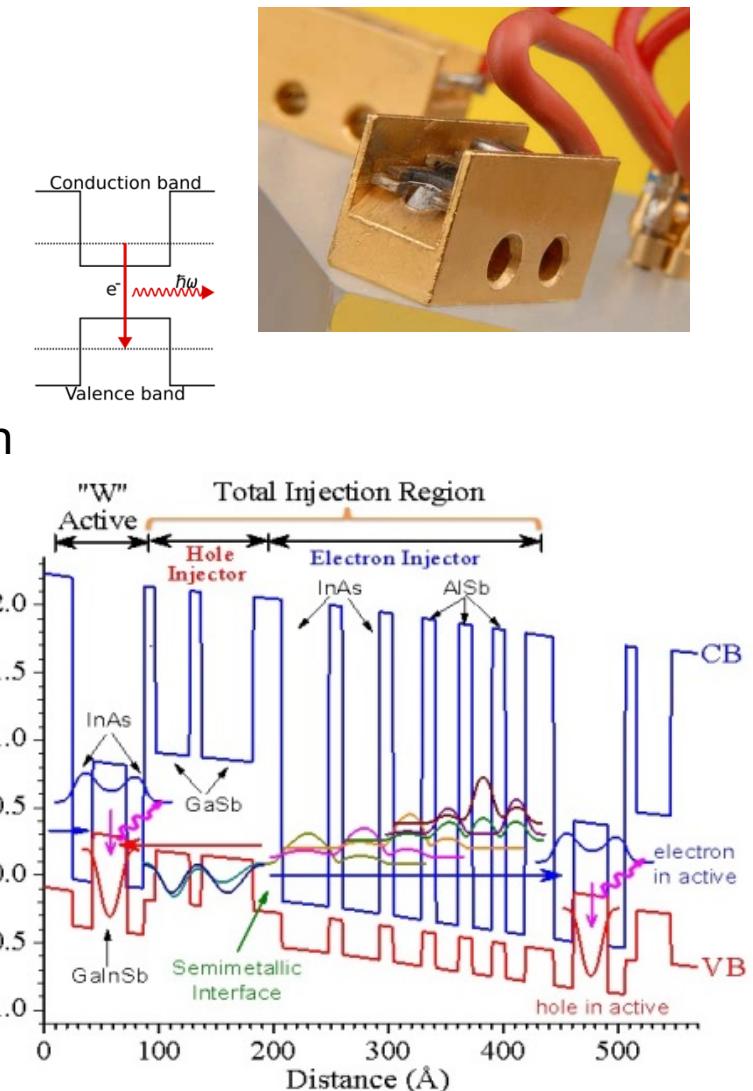
## II.1 Mid-IR sources

- Non-coherent sources:
  - Black body: Any heated object, non-coherent not very powerfull.
- Coherent sources
  - Gaz laser : CO (5-6 $\mu$ m) CO<sub>2</sub>(9-10 $\mu$ m). Powerful, not compact.
  - Non-linear effects based sources: OPO for instance, pulsed, high power, expensive complex systems.
  - Semiconductor lasers : Il y a le choix!



## II.1 Mid-IR sources : Semiconductors

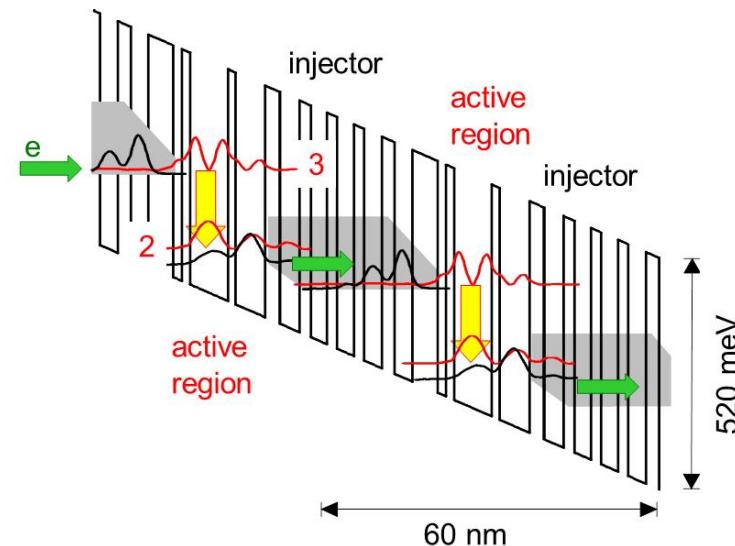
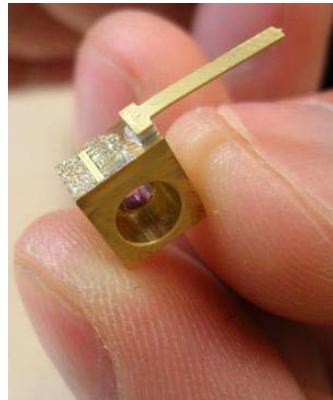
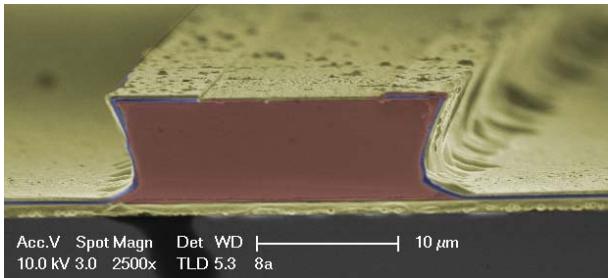
- Lead salt lasers : (3-30 $\mu$ m)
  - High spectral range, low power emission, not very reliable, Cryogenic temperature operation.
- Inter-band lasers : (0,9-5 $\mu$ m)
  - Optical transition between valence and conduction band: Room temperature operation  $\lambda < 3\mu\text{m}$ . Ex: GaInAsSb/AlGaAsSb.
- Quantum cascade laser (3-24 $\mu$ m ar THz):
  - Transition inter-sous-bandes en bande de conduction.
- Interband Quantum cascade lasers: (3-12 $\mu$ m)
  - As QCLs , but optical transitions occurs between valence and conduction band;



## II.1 Les sources Mid-IR: QCL

Émission: Laser à cascade quantique (QCL)

- Sources compactes qui couvrent une large gamme spectrale, dans le moyen-infrarouge et dans le THz.



## II.4 QCL: Principles

---

II.4.1 Active region

II.4.2 Optical confinement.

Dielectric waveguide

Plasmonic waveguide

II.4.3 Optical cavities

Fabry-Pérot

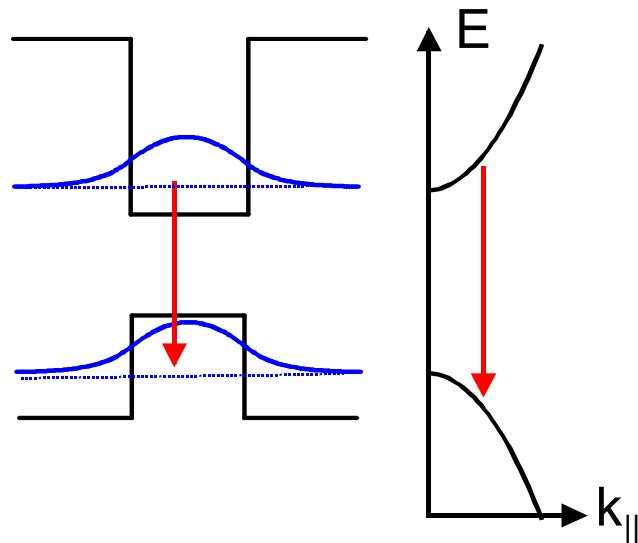
DFB

External cavity

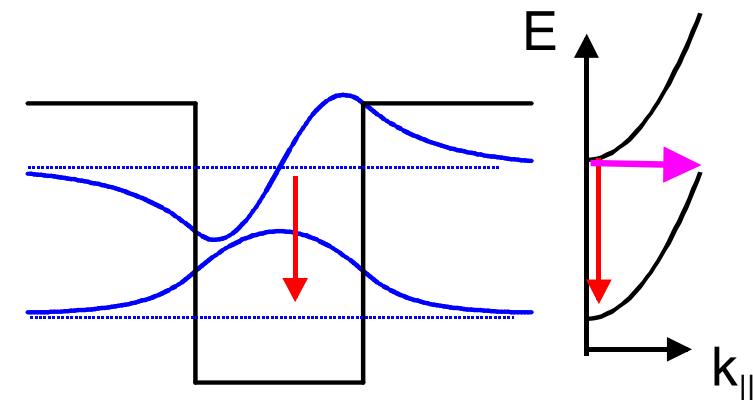
Photonic crystals

## II.1 Inter-sub-band transition

**Interbande:**



**intersousbande:**

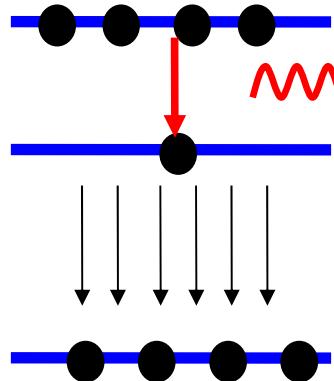


- Energie du photon limitée
- Densité d'état jointe 2D
- Long temps de vie ( $\sim 1\text{ns}$ )

- Flexibilité dans la conception des fonctions d'ondes
- Densité d'état jointe 1D
- Temps de vie court ( $\sim 1\text{ps}$ )

## II.4.2 Région Active : Principle

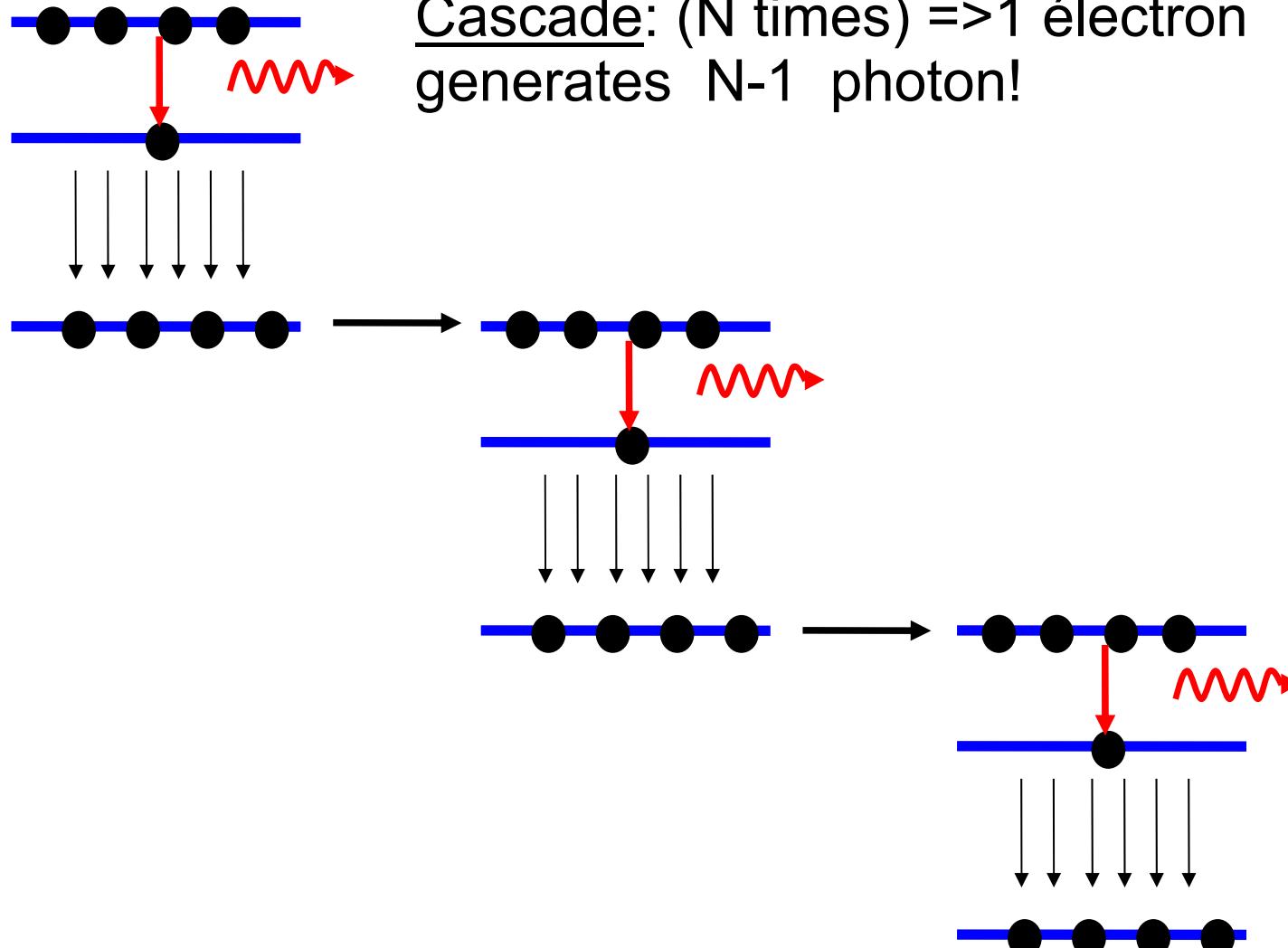
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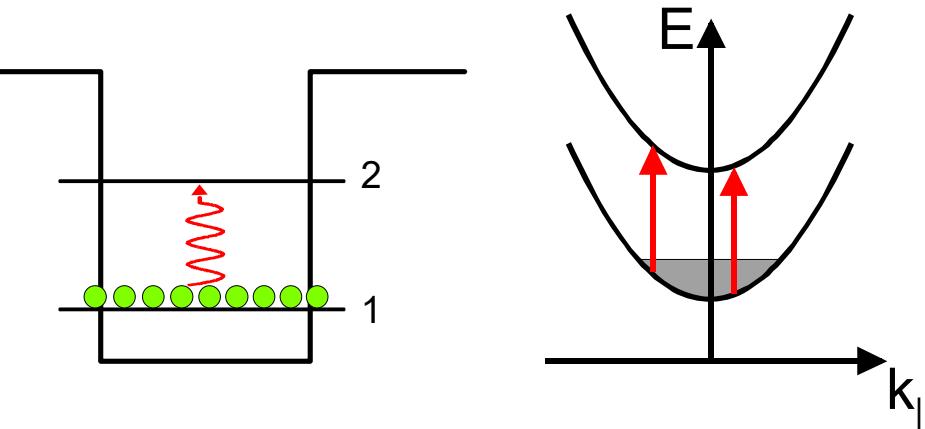
Optical Transition (radiative)

Rapid relaxation of  
électrons to the ground  
state => Inversion of  
population

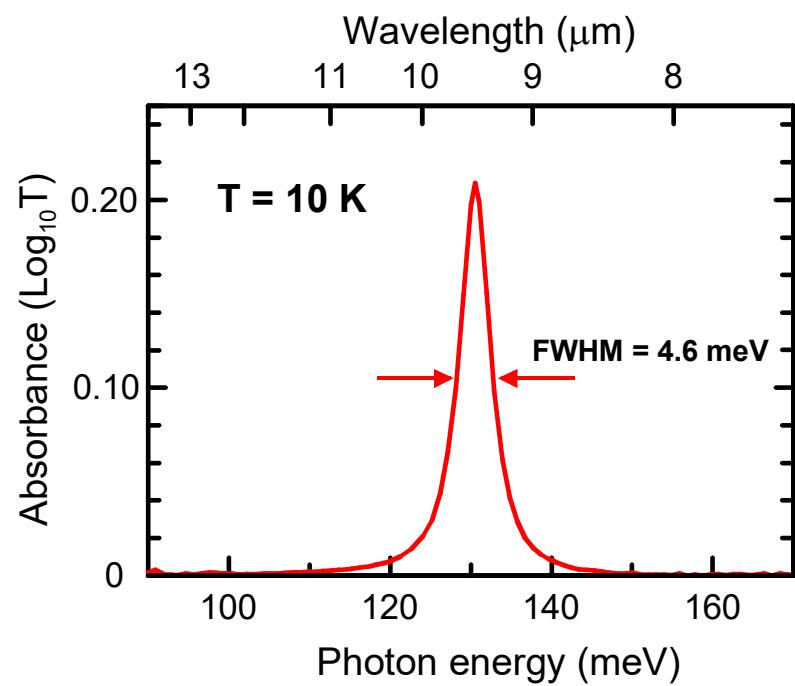
## II.4.2 Un électron génère plusieurs photons



## II.4.2 Absorption/Emission Inter-sous-bandes



$$E_{n,k} - E_{m,k} = \Delta E_{nm} \quad \forall k$$



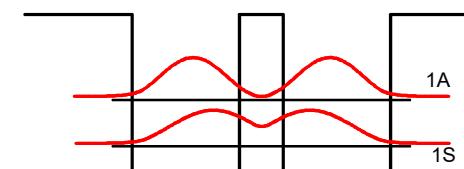
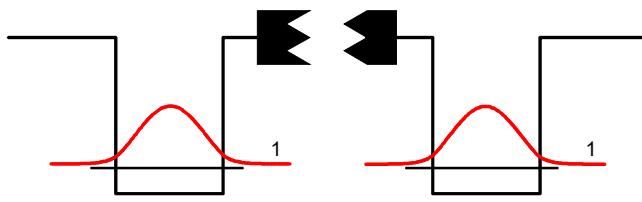
Lorentzien shape

Empirical rule:  $\delta\omega/\omega \approx 10\%$

## II.4.2 Coupled quantum wells: as in molecule

Quantum engineering of intersubband transitions is enabled by coupling of quantum wells through thin tunneling barriers:

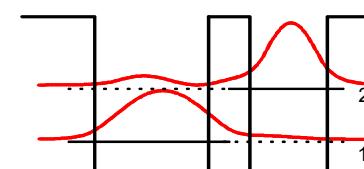
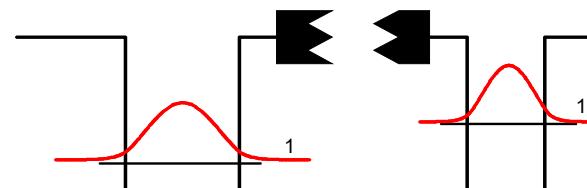
Symetric coupled wells



doublet  
symetric and asymmetric

Molécule d'hydrogène

Asymmetric coupled wells



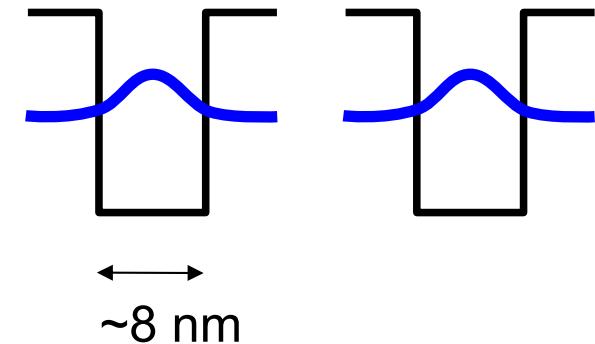
Hybridation des orbitaux avec  
numéros quantiques différents

## II.4.2 How to build Active region: step 1

---

### Quantum tools:

- quantum wells and barriers  
0.5 – 20 nm
- Transition mechanisms:
  - Radiative transition ( $\sim\mu\text{s}$ )  
(spontaneous emission)



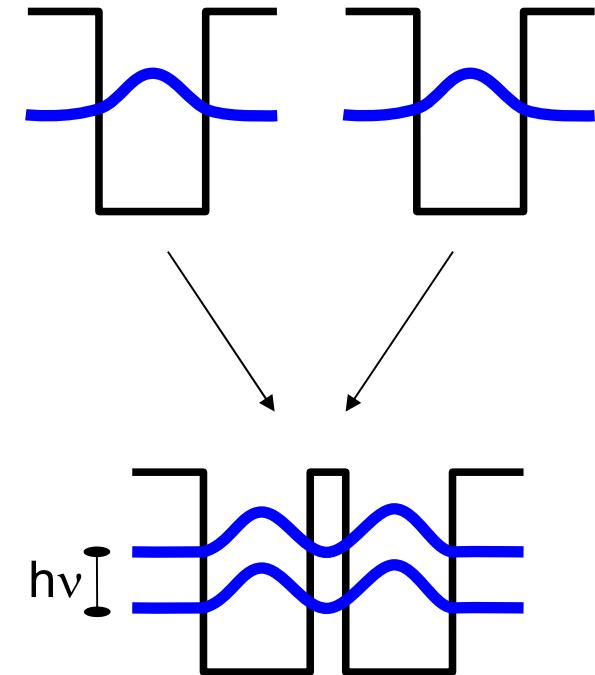
Well: GaAs  
Barrier: Al<sub>0.15</sub>Ga<sub>0.85</sub>As

# Step 2: coupled quantum wells

---

## Quantum tools:

- quantum wells and barriers  
0.5 – 20 nm
- Transition mechanisms:
  - Radiative transition ( $\sim \mu\text{s}$ )  
(spontaneous emission)

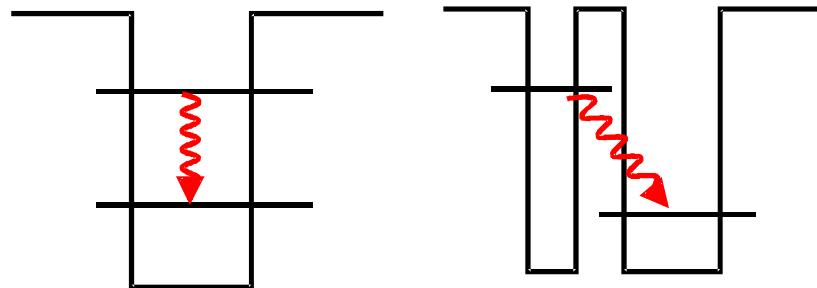


The barrier thickness sets the photon energy!

Very convenient technique especially at long wavelengths!

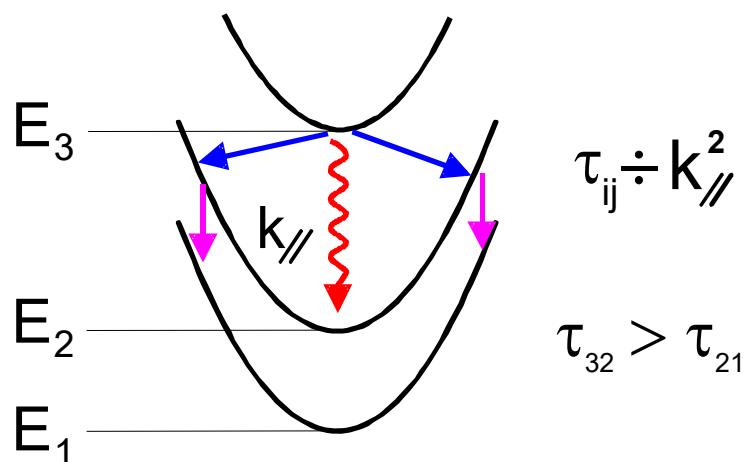
## II.4.2 Life time engenering!

---



Diagonal Transition

Forcing the electrons to go through a tunnel barrier



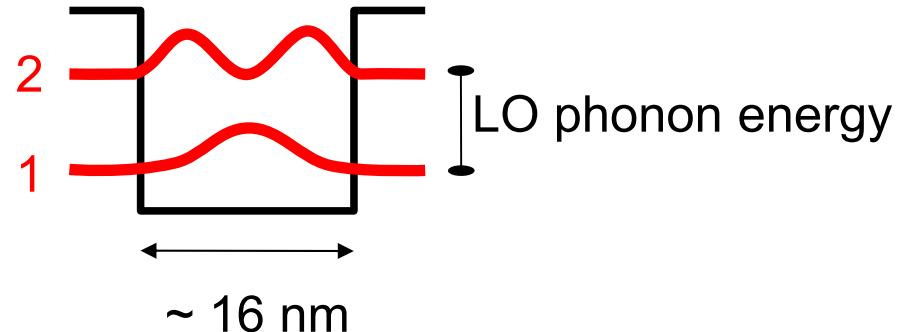
Optical phonon resonance:  
The lifetime of an electronic state becomes extremely short if the **resonant emission** of an optical phonon is possible

# Step 3: Population inversion

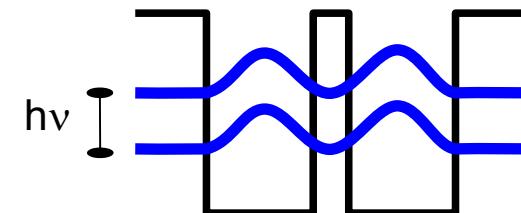
## Quantum tools:

- quantum wells and barriers  
0.5 – 20 nm
- Transition mechanisms:
  - Radiative transition ( $\sim \mu\text{s}$ )  
(spontaneous emission)
  - LO phonon emission ( $\sim \text{ps}$ )  
possible (and fast!) if  
 $\Delta E > 36 \text{ meV}$  ( $T=0$ )
  - electron-electron scattering ( $\sim \text{ps}$ )  
faster when  $\Delta E$  decreases
- Transport: resonant tunneling

*Relaxation rapide du niveau 2 à 1*



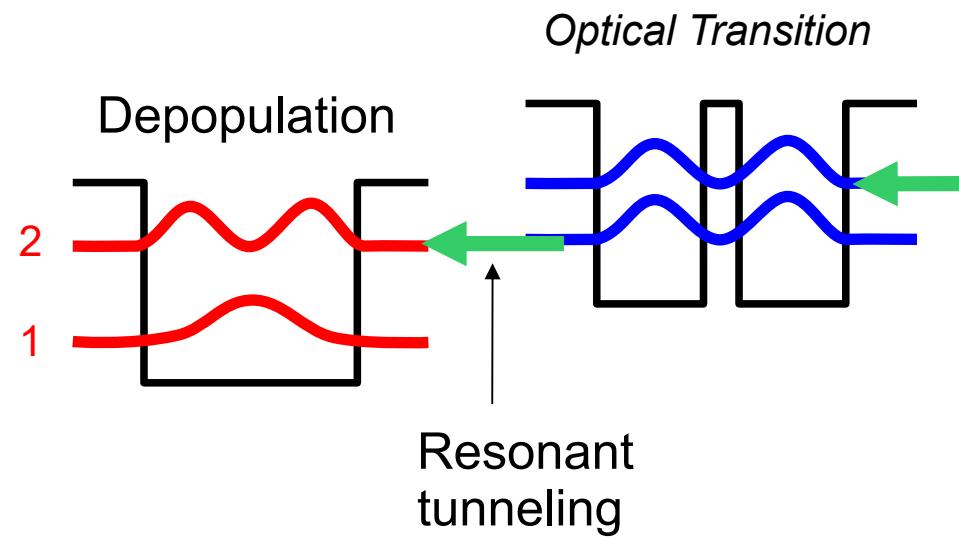
*Optical Transition*



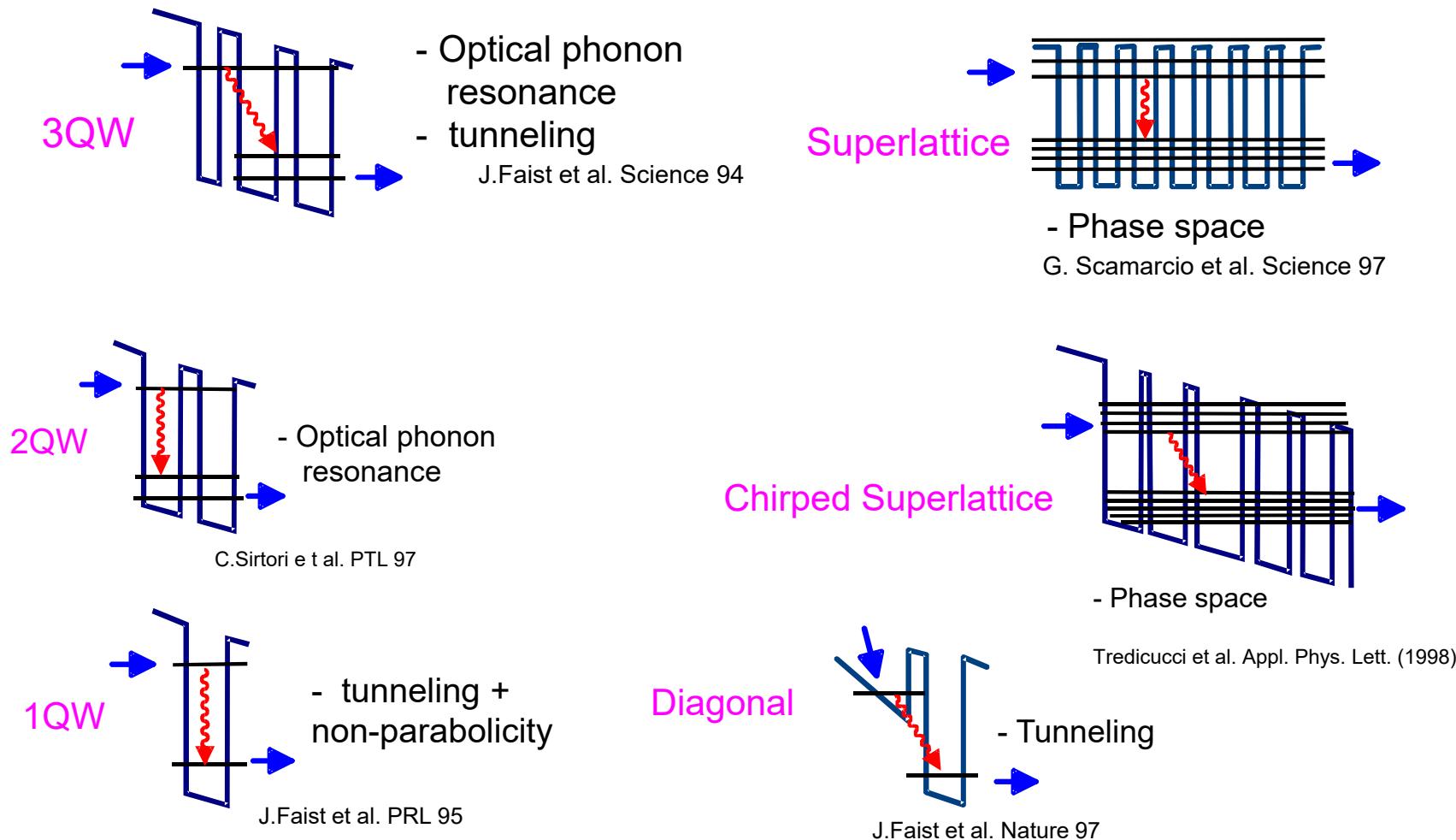
# Step 4: resonant tunnel effect for injection/extraction of carriers

## Quantum tools:

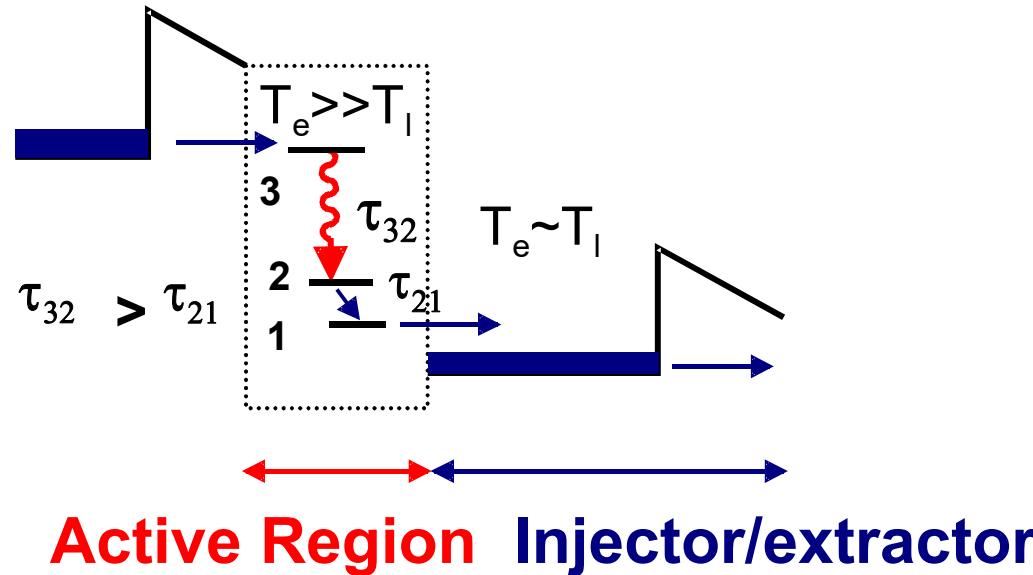
- quantum wells and barriers  
0.5 – 20 nm
- Transition mechanisms:
  - Radiative transition ( $\sim \mu\text{s}$ )  
(spontaneous emission)
  - LO phonon emission ( $\sim \text{ps}$ )  
possible (and fast!) if  
 $\Delta E > 36 \text{ meV}$  ( $T=0$ )
  - electron-electron scattering ( $\sim \text{ps}$ )  
faster when  $\Delta E$  decreases
- Transport: resonant tunneling



## II.4.2 Different kinds of active region



## II.4.2 In summary



Il faut:

- Population inversion  $\rightarrow$  **Active Region**
- Transport of carrier for next period  $\rightarrow$  **Injector/extractor**

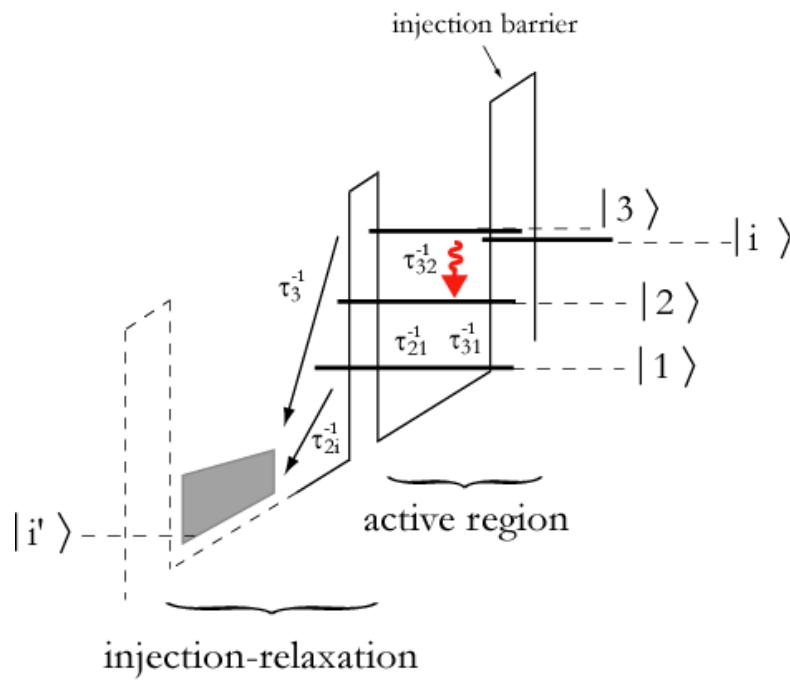
J. Faist, F. Capasso, C. Sirtori, D. L. Sivco, A.L. Hutchinson, A.Y. Cho, Science 264, 477 (1994)

## II.4.2 Threshold condition

$$G_p = \frac{4\pi e^2}{\epsilon_0 n \lambda} \frac{z_{32}^2}{2\gamma_{32} L_p} \Gamma(n_3 - n_2)$$

dipole matrix element  
spontaneous emission linewidth  
period length

$\boxed{\quad} = g_c$



Rate equations:

$$\tau_3^{-1} = \tau_{32}^{-1} + \tau_{31}^{-1} + \tau_{esc}^{-1}$$

$$\tau_2^{-1} = \tau_{21}^{-1} + \tau_{2i}^{-1}$$

$$J_{thresh} = \frac{e}{\tau_3} \frac{(\alpha_w + \alpha_m)/g_c + n_2^{\text{therm}}}{1 - \tau_2/\tau_{32}}$$

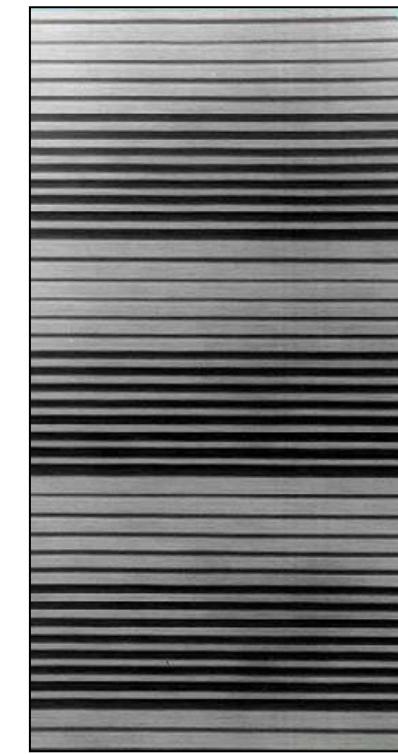
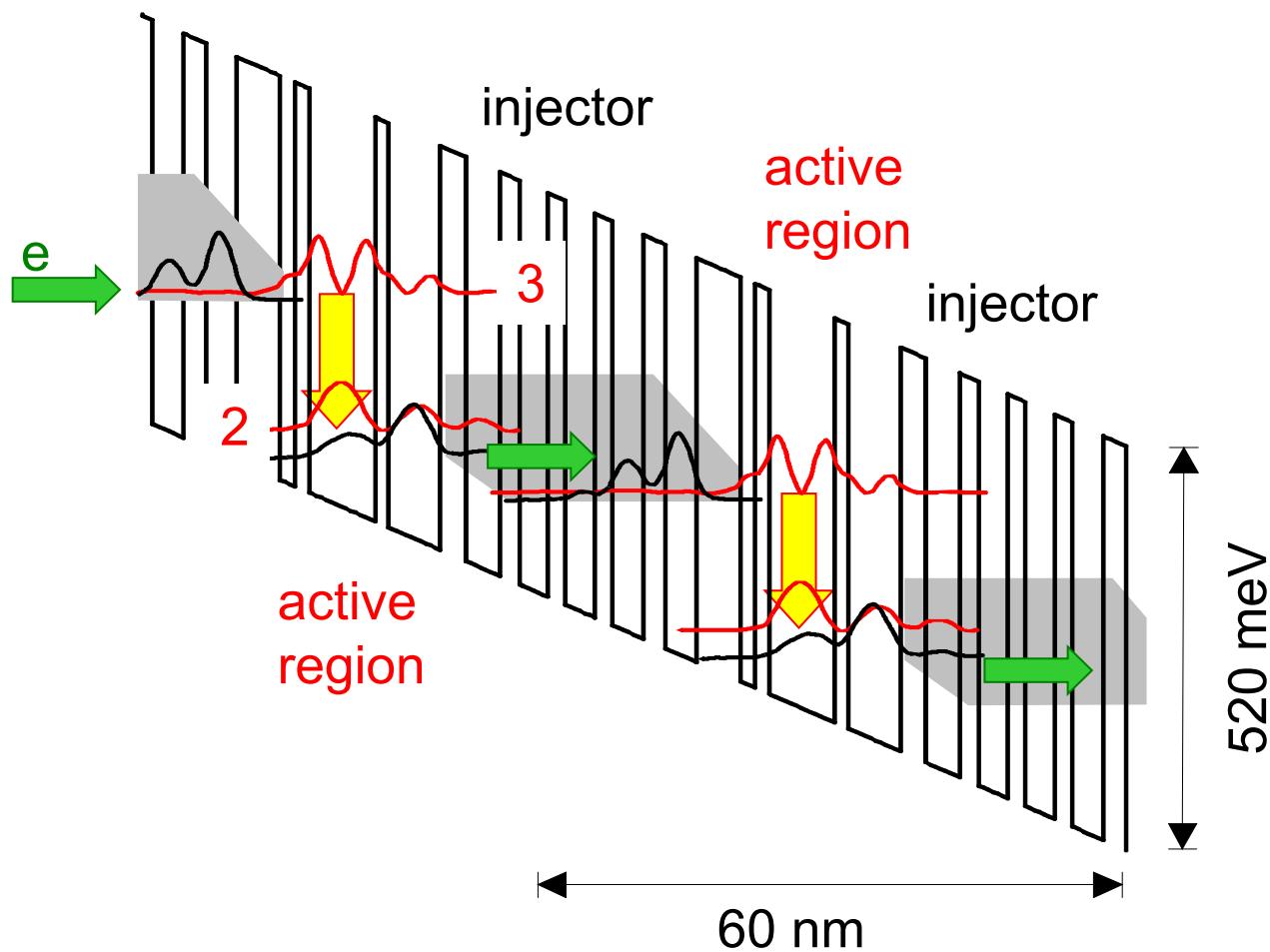
Maximize  $\tau_3^{-1}, \tau_{32}^{-1}$

Minimize  $\tau_2^{-1}$

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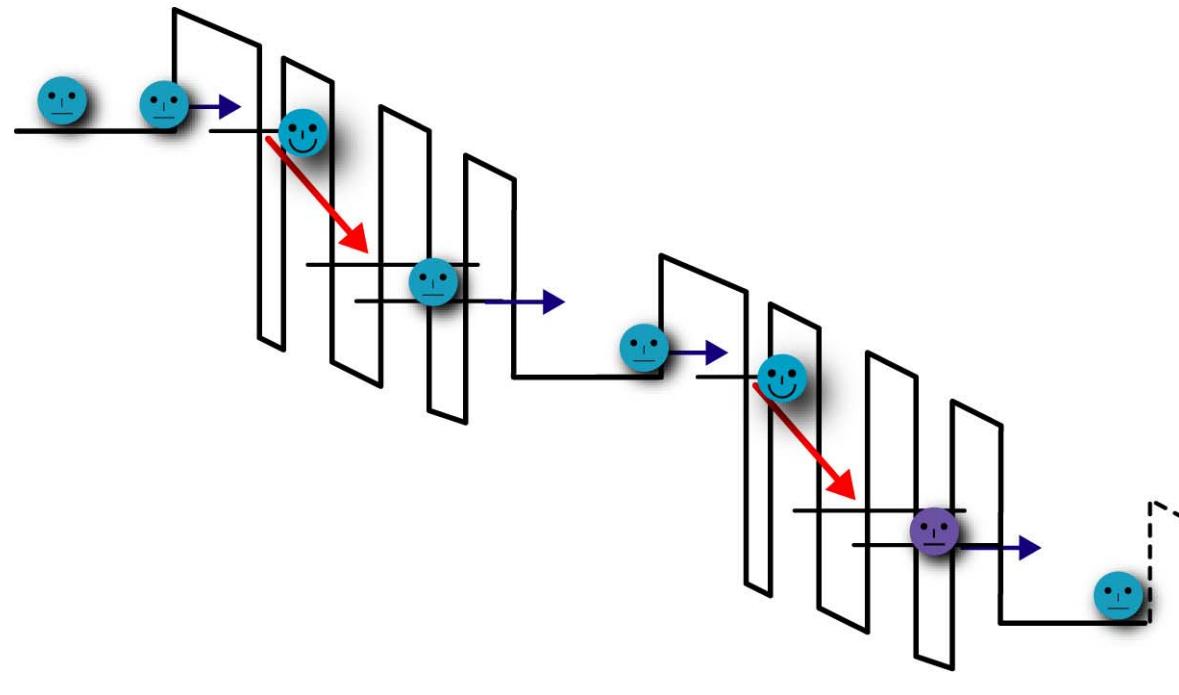

$$\begin{aligned}
 \frac{\partial N_3}{\partial t} &= \frac{J}{q} - \frac{N_3}{\tau_3} - \sigma S(N_3 - N_2) \\
 \frac{\partial N_2}{\partial t} &= \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_2} + \sigma S(N_3 - N_2) \\
 \frac{\partial S}{\partial t} &= [\sigma(N_3 - N_2) - \bar{c}\alpha_{tot}] S.
 \end{aligned}$$

## 4.2 Typical AR under bias (Mid-IR)



## II.4.2 Cascade

---



-> 1 électron peut générer plusieurs photons

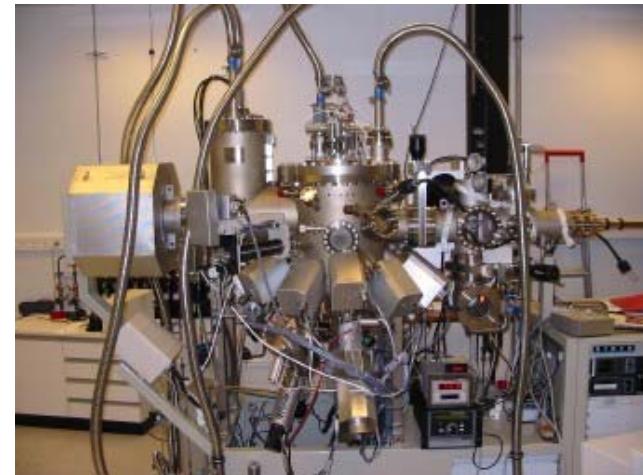
J. Faist et al., Science **264**, 553 (1994)

## II.2 Technologie de croissance

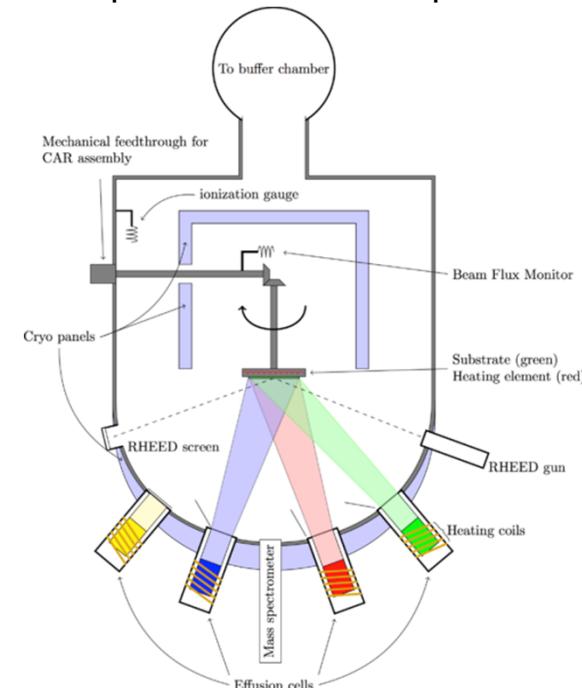
- **Épitaxie par jets moléculaire**

- MBE pour Molecular Beam Epitaxy
- Vitesse d'environ une monocouche atomique par seconde.
- Sous Ultra ultravide ( $10^{-9}$ - $10^{-11}$ mBar) « ultra high vacuum ».
- Envoyer un ou plusieurs jets moléculaires vers un substrat préalablement choisi pour réaliser une croissance épitaxiale.
- C'est le système de prédilection pour la croissance des QCL.cc

**Contrôle de la croissance à une monocouche près!!**



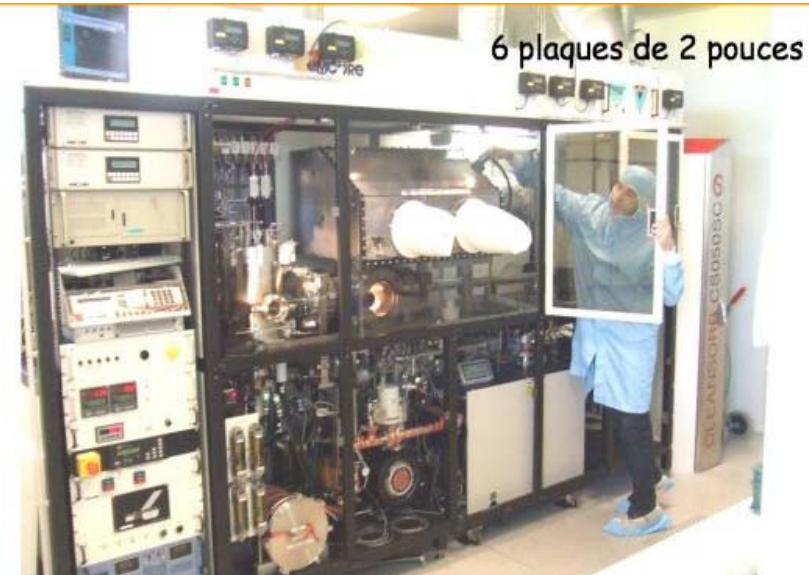
Bâti d'épitaxie RIBER Compact 21 LPN-CNRS



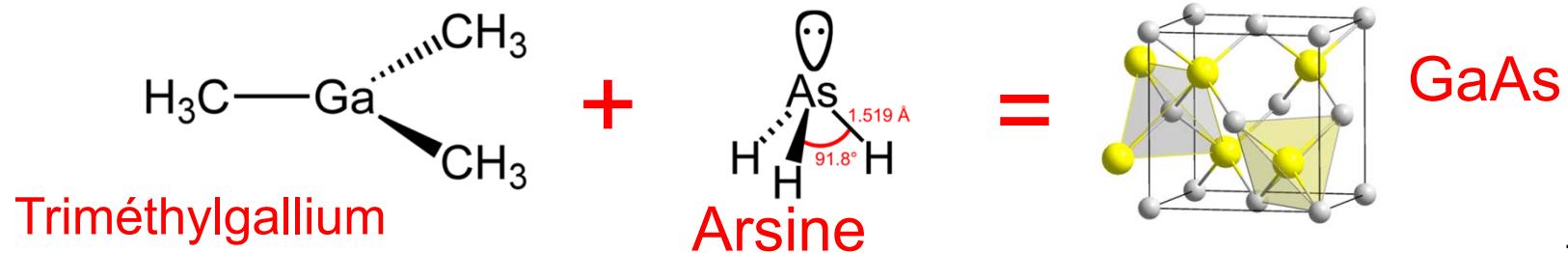
## II.2 Technologie de croissance

### • Épitaxie en Phase Vapeur aux Organométalliques

- Le substrat est chauffé et balayé par un gaz vecteur.
- Les éléments à épitaxier sont sous forme de molécules appelées précurseurs.
- Si les conditions sont bien choisies, les molécules se pyrolysent au contact du substrat chauffé
- Les résidus des précurseurs sont évacués par le gaz vecteur.
- Croissance plus rapide que la MBE, et de plus en plus maîtrisée!
- Pas besoin d'un vide poussé!



VEECO TurboDisc D180 (LPN-CNRS)

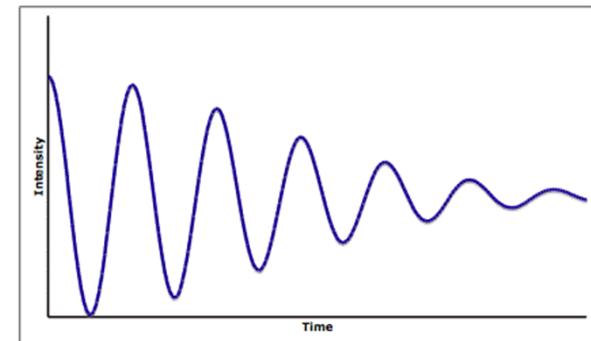
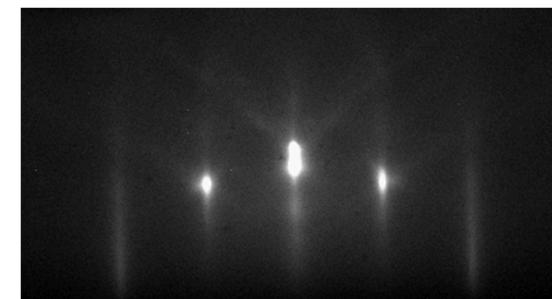
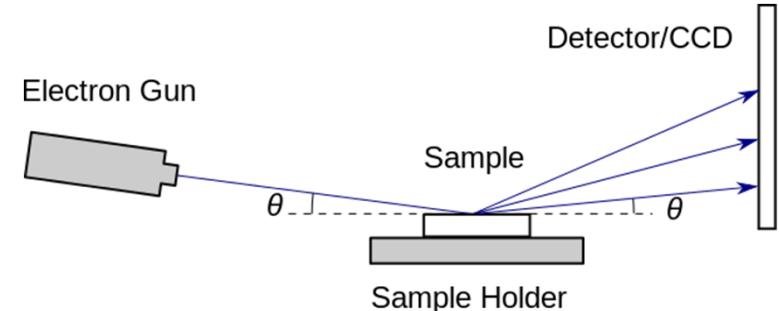


## II.2 Technologie de croissance

- Caractérisations structurales des couches: RHEED in situ

- Reflection high-energy electron diffraction

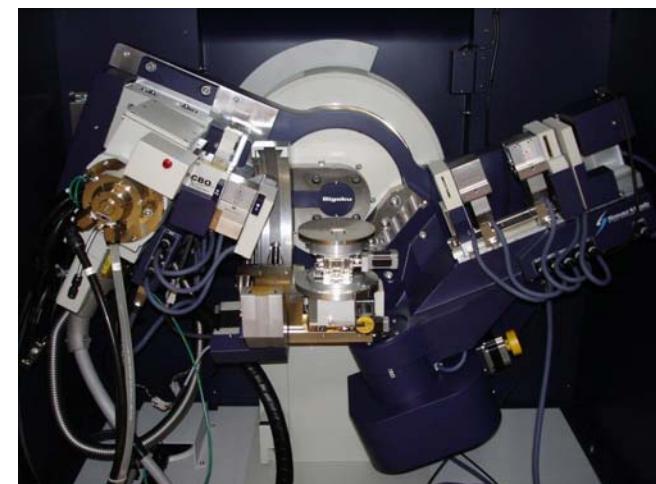
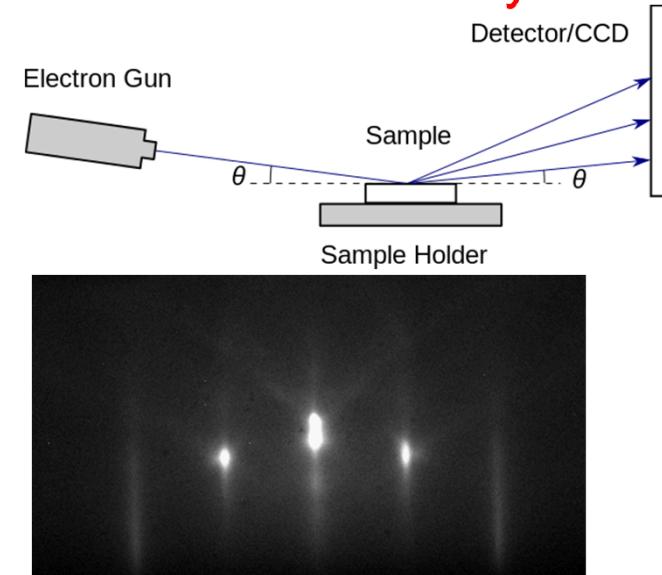
- Très utilisée en croissance MBE
- Contrôle in-situ (pendant la croissance)
- Les intensités des taches individuelles sur le motif RHEED fluctuent d'une manière périodique à la suite de la couverture de la surface relative de la couche mince en croissance.
- Chaque période correspond à la formation d'une couche atomique.
- La période d'oscillation est très dépendante du système de matière,
- Données empiriques pour corrélérer les oscillations de l'intensité pour contrôler la croissance.



## II.2 Technologie de croissance

- Caractérisations structurales des couches: Diffraction RayonX

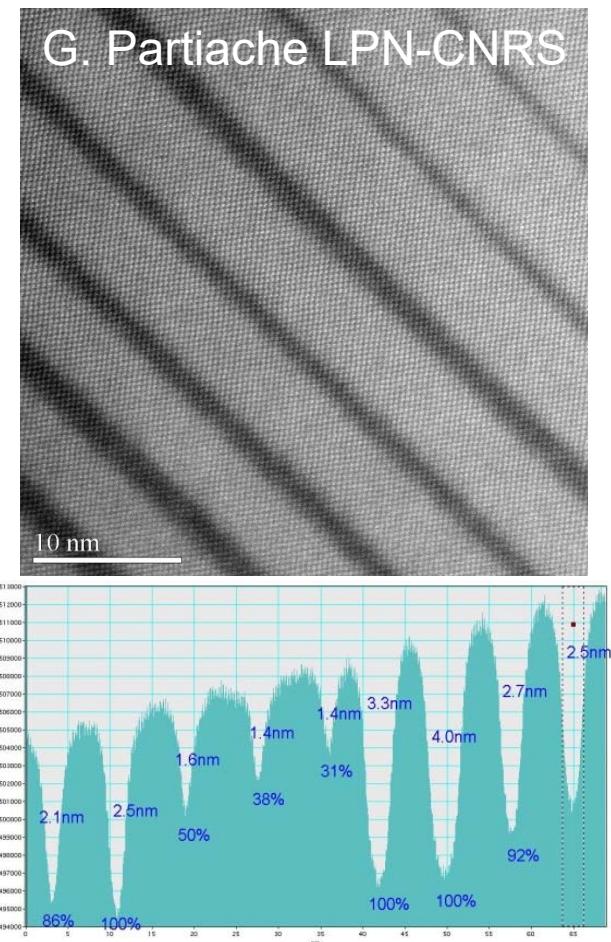
- La cristallographie aux rayons X
- Détermination de l'arrangement des atomes d'un cristal, dans laquelle un faisceau de rayons X rencontre le cristal provoquant la dispersion du faisceau lumineux dans des directions spécifiques.
- Par la mesure des angles et de l'intensité des rayons réfractés, il est possible d'obtenir une image tridimensionnelle de la densité électronique dans le cristal. À partir de cette densité, la position moyenne des atomes du cristal peut être déterminée, ainsi que leurs liaisons chimiques, leur entropie et d'autres informations.



## II.2 Technologie de croissance

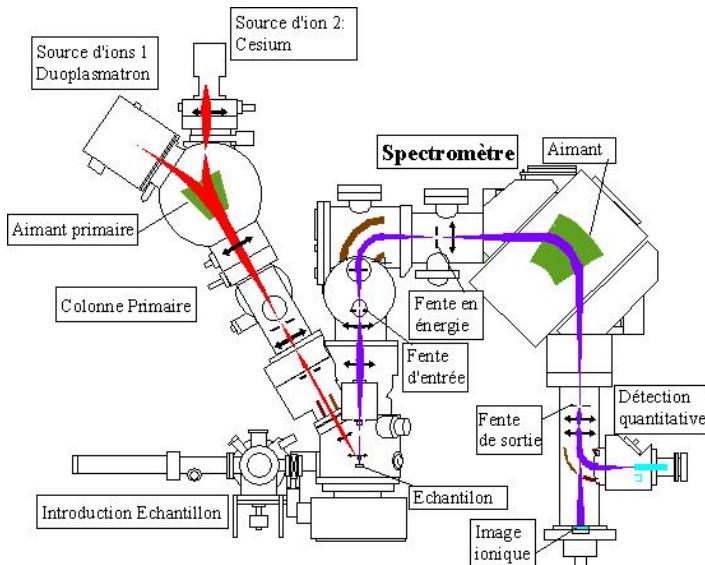
- Caractérisations structurales des couches: TEM

- Microscopie électronique à transmission:
  - Un faisceau d'électrons est « transmis » à travers un échantillon très mince.
  - Les effets d'interaction entre les électrons et l'échantillon donnent naissance à une image.
  - La résolution peut atteindre 0,08 nanomètre!!
  - Associée à l'analyse rayonX , l'interprétation des images permet une analyse poussée des couches, épaisseurs alliages...



## II.2 Technologie de croissance

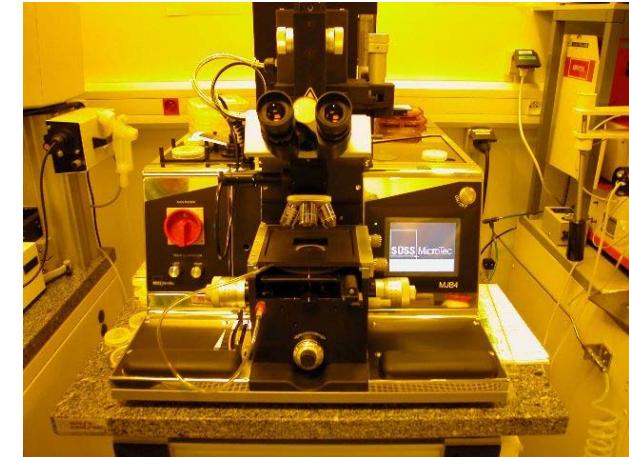
- Caractérisations des croissances: Contrôle du dopage
  - SIMS:
    - Spectrométrie de masse à ionisation secondaire
    - Mesure destructive, mesure quantitative des espèces chimique (les dopants n'est pas forcément le dopage!)
  - Effet Hall:
    - Mesure électrique, effet % au dopage de la couche mesurée.
  - Autres techniques électriques...



## II.2 Technologie de fabrication

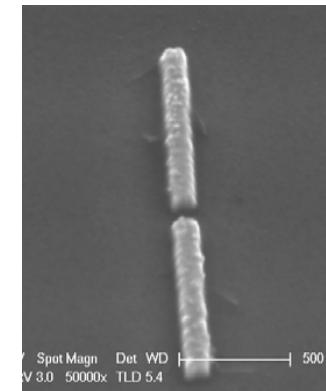
- **Lithographie**

- Permet de transférer un masque vers un substrat.
- Les motifs du masque transférés deviendront par la suite les différentes zones des composants (Guide, contact isolants....)



- Il existe deux principales catégories:

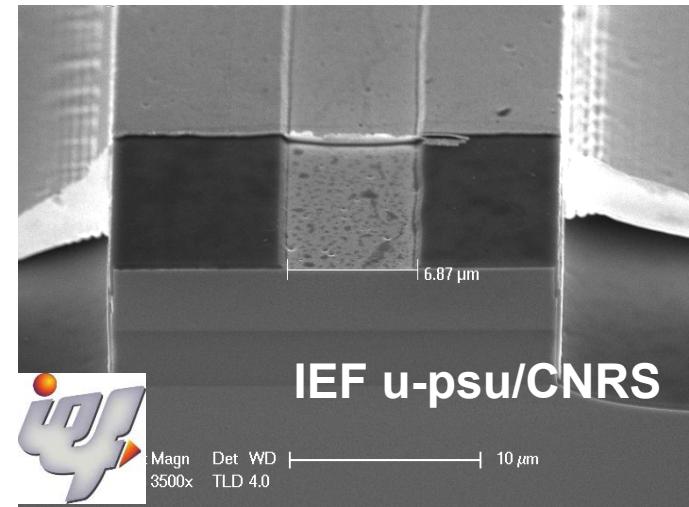
- **Lithographie optique:** Masque physique (Cr sur quartz), résine photo sensible (UV), positive ou négative selon les étapes de fabrication. Résolution de qlq  $\mu\text{m}$  (donnée par la limite de diffraction de la lumière).
- **Lithographie électronique:** Masque virtuel donné par le mvt relatif du faisceau d'é par rapport à la surface de l'échantillon, résine sensible aux charges. Résolution de qlq nanomètre!



## II.2 Technologie de fabrication

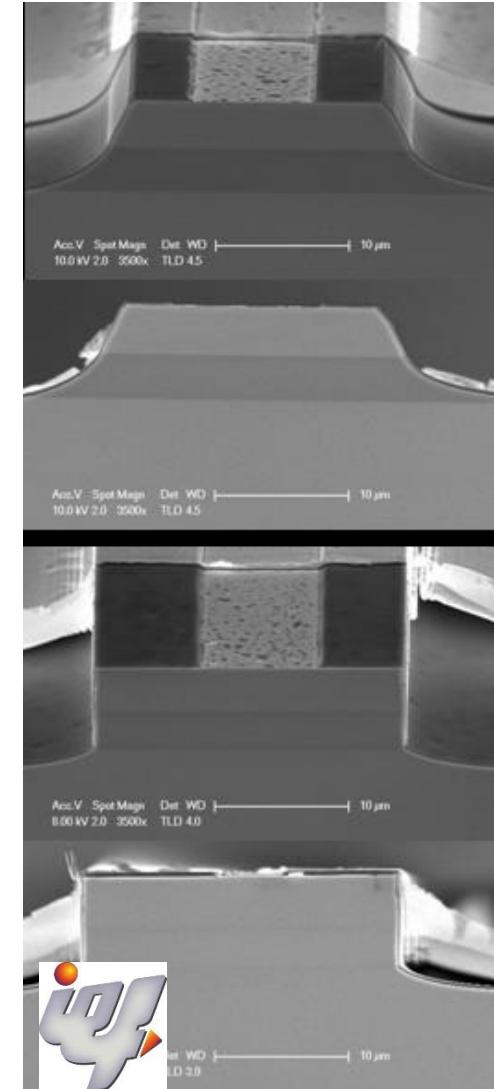
- **Dépôt de couches minces:**

- **Métaux:** permet de déposer les contacts électriques sur les couches de semi-conducteurs (contact Ohmiques). Évaporation sous vide ou co-pulvérisation cathodique.
- **Isolants:** Le dépôt de couches d'isolant ( $\text{SiO}_2$ ,  $\text{Si}_3\text{N}_4$ ,  $\text{Al}_2\text{O}_3$ ...) permet d'isoler électriquement les dispositifs et de pouvoir injecter le courant correctement. Technique PECVD (Plasma Enhanced Chemical Vapor Deposition).
- **Miroir HR:** pour les QCL le dépôt de couches minces permet aussi de faire des miroir de haute réflectivité sur les facettes du laser.



## II.2 Technologie de fabrication

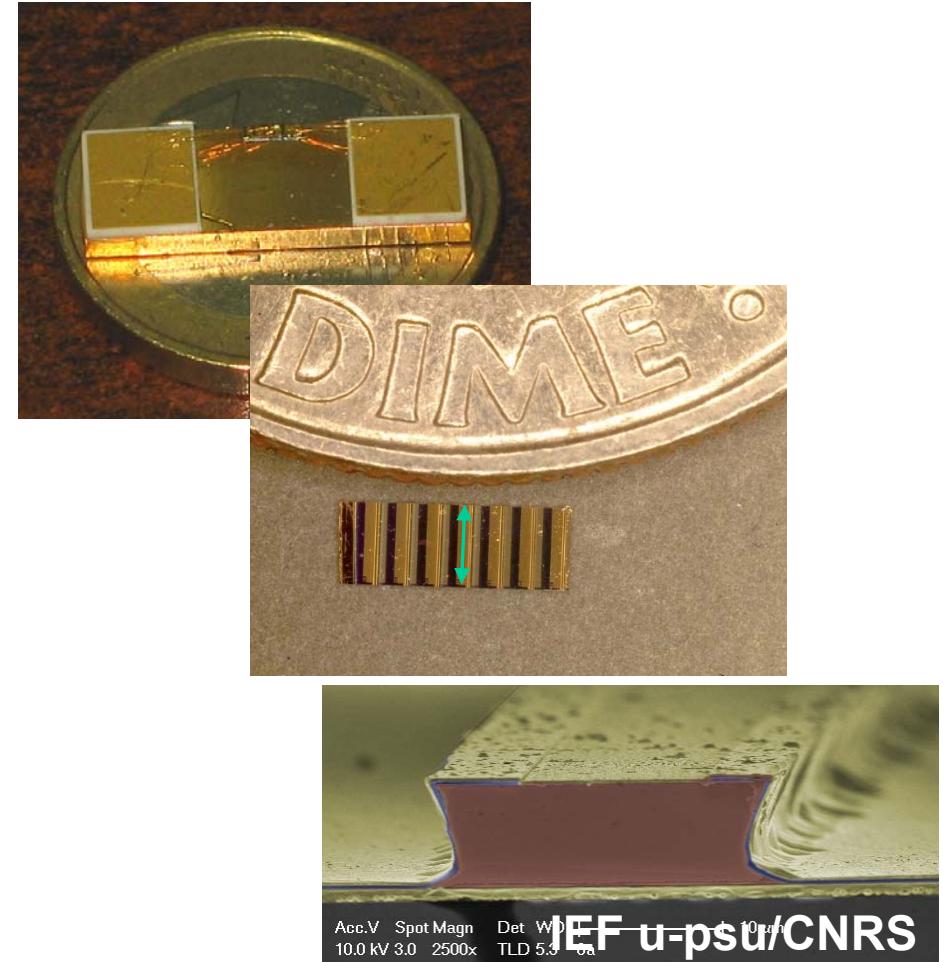
- **Gravure:**
  - Elle permet d'enlever de la matière sur la surface de l'échantillon, des zones de l'échantillon peuvent être protéger ou pas (masque de protection). Gravure de Semi-conducteur, isolants, métaux, nettoyage...
  - **Gravure Humide:** Réaction purement chimique, en milieux aqueux. Pas de contrôle précis sur la vitesse de gravure verticale et latérale. Sensibilité à l'orientation du cristal, vitesse selon les concentration de la solution de gravure.
  - **Gravure sèche:** Plasmas réactifs (ou inertes). En plus des réaction chimique, un plasma réactifs permet de contrôler la réaction (vitesse de gravure verticale >> vitesse de gravure latérale). Technique ICP, RIE.



## II.2 Technologie montage

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- Amincissement
- Clivage des facettes
- Collage sur embases
- Fils micro soudés pour l'injection électrique

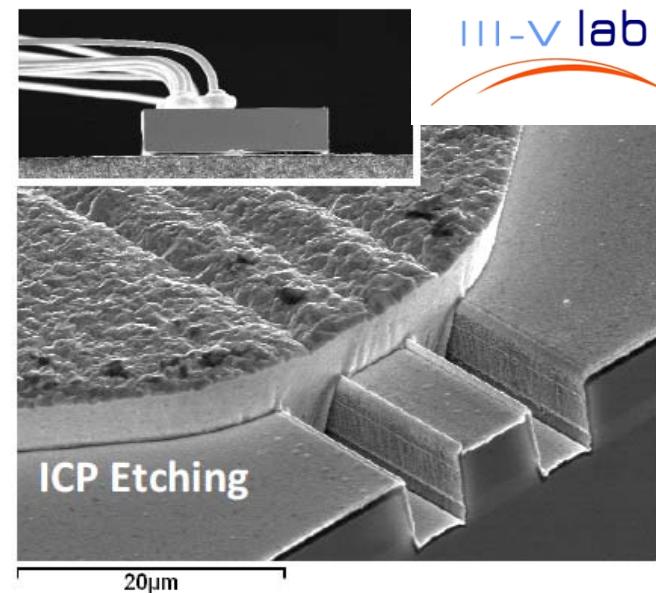


## II.2 Techniques de montage

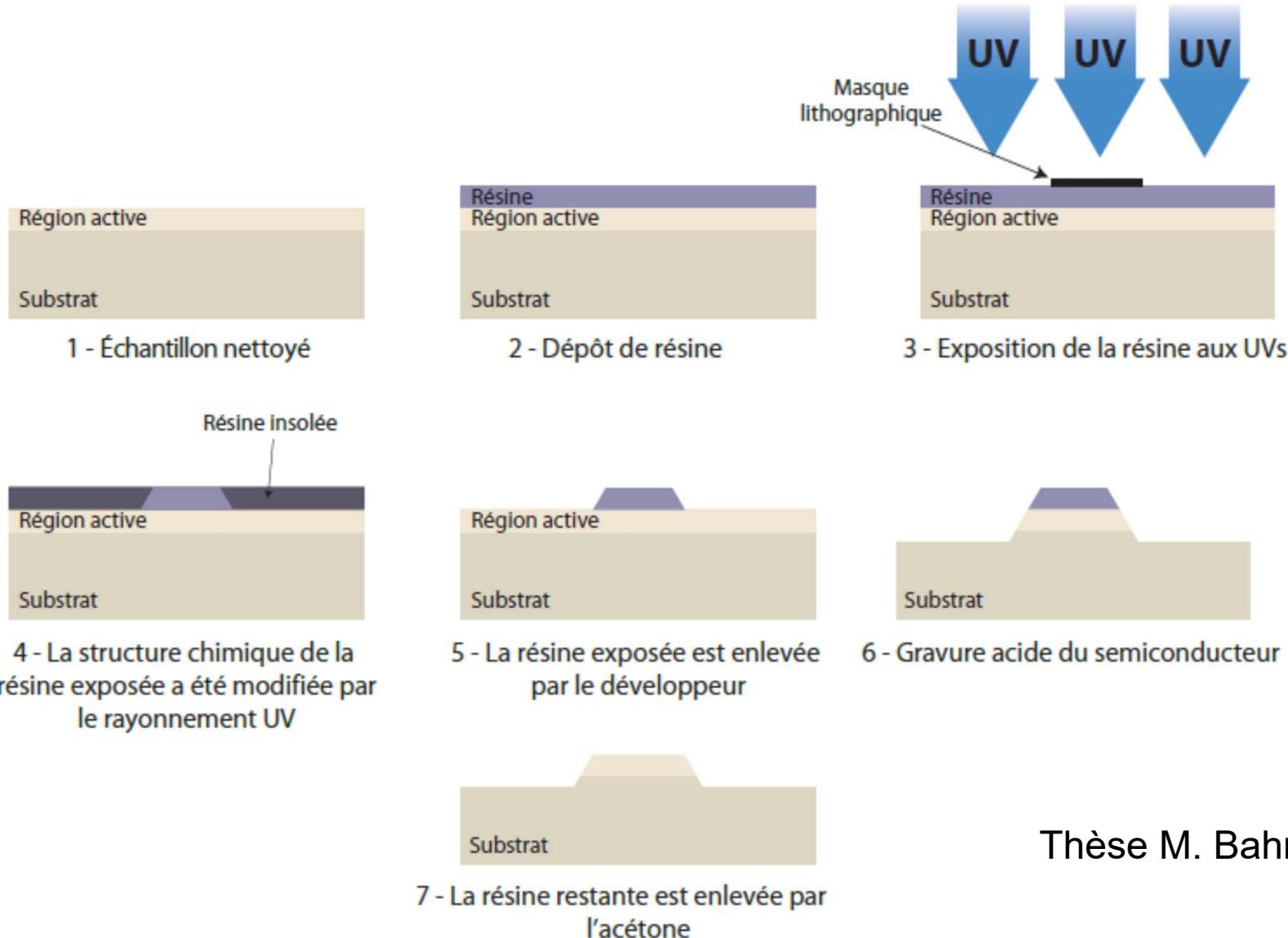
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- Gérer la dissipation thermique

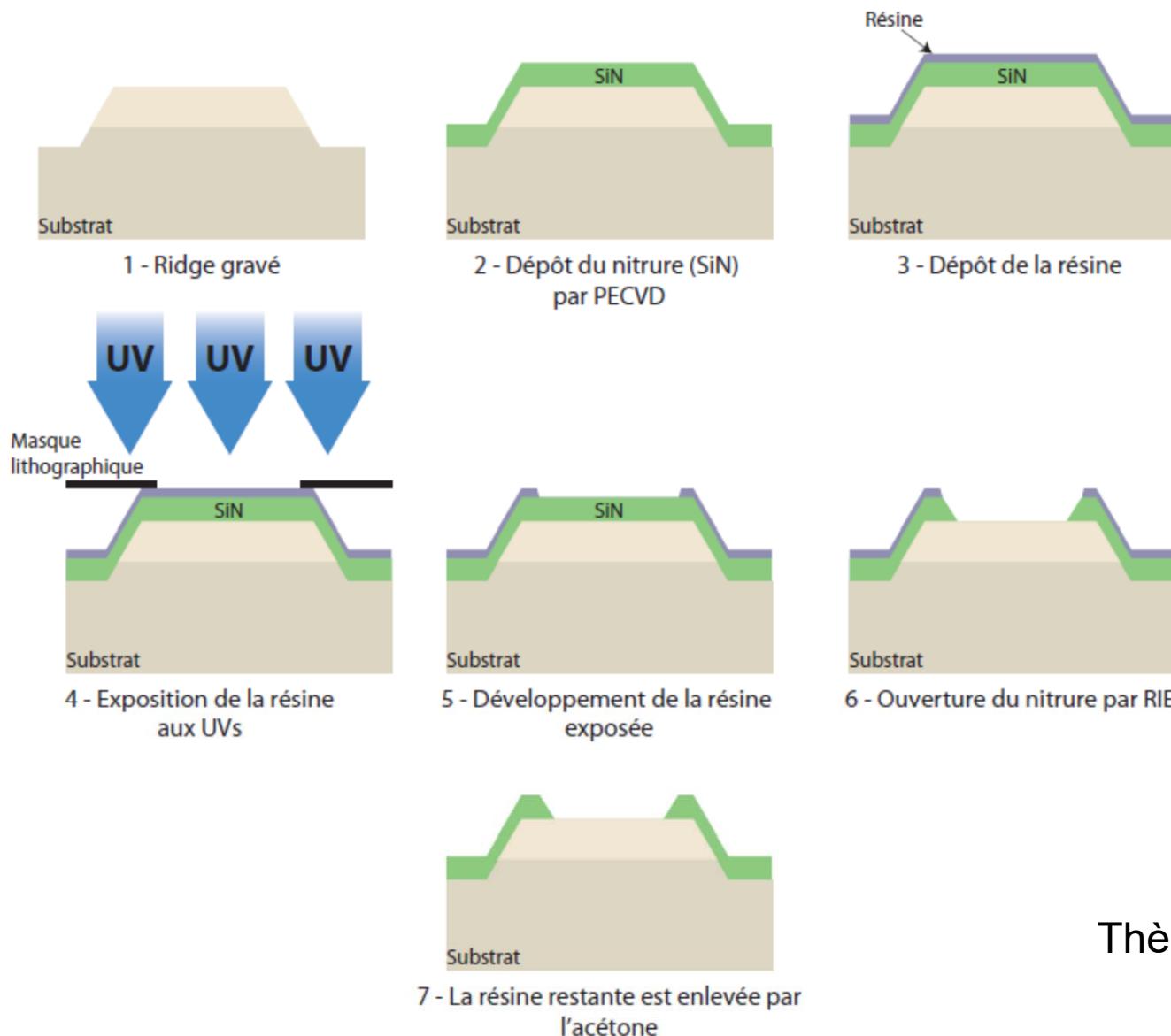
- Pour un fonctionnement en mode d'injection continu (CW).
- Technologie double tranche
- Épaississement du contact face avant (croissance électrolytique de l'Or).
- Montage d'un échantillons contenant un laser unique en « Episide down »



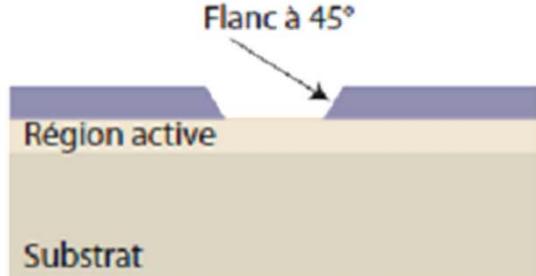
## II.2 Étapes de fabrication (1)



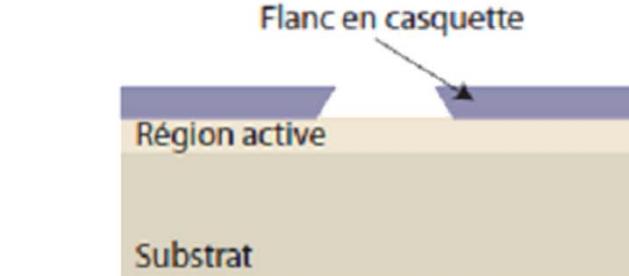
## II.2 Étapes de fabrication (2)



## II.2 Étapes de fabrication (3)



Développement d'une résine positive



Développement d'une résine négative

Dépôt métallique sur une résine positive



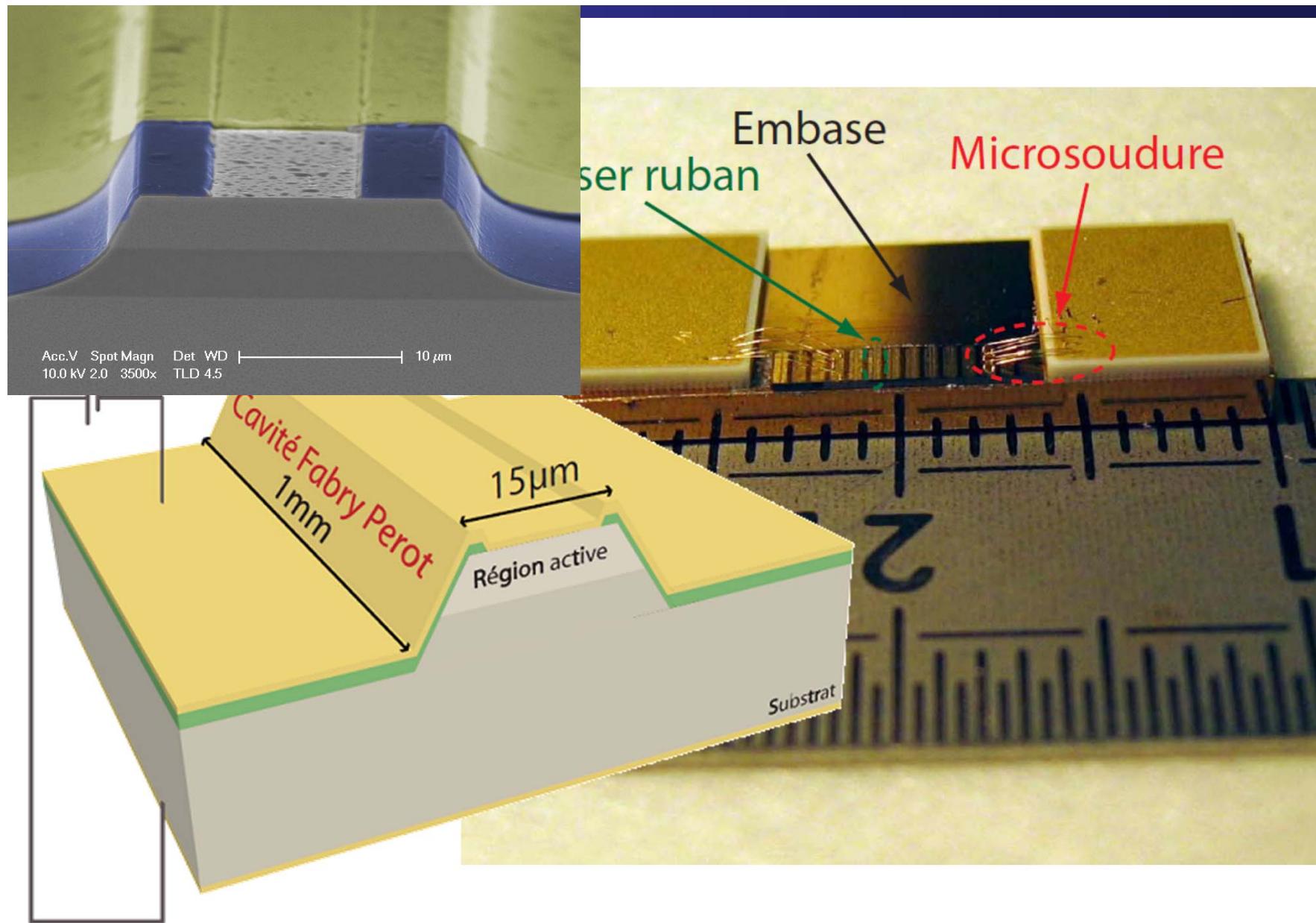
Dépôt métallique sur une résine négative

*Lift-off*  
extrêmement difficile

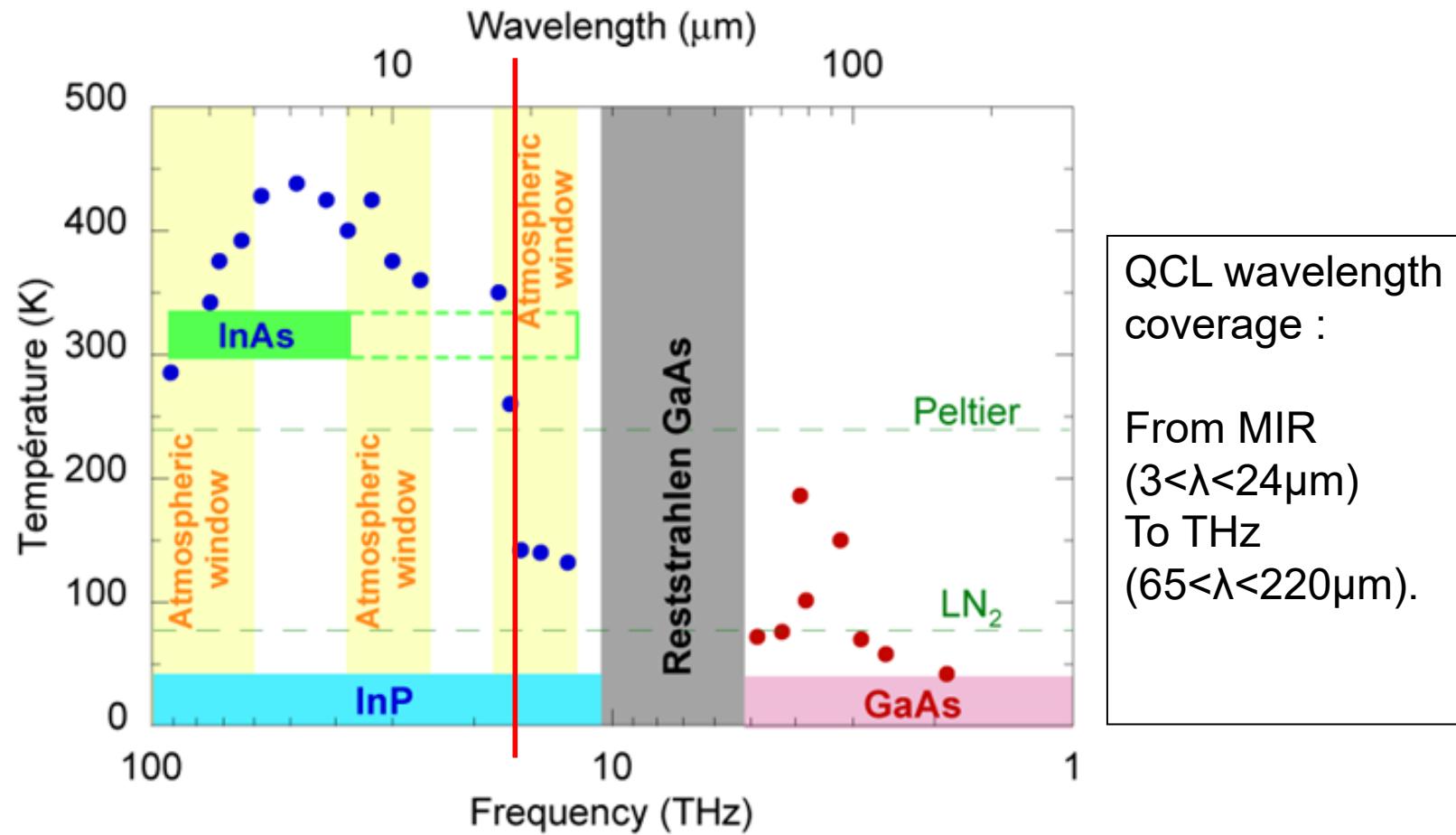


*Lift-off*

## II.2 Étapes de fabrication (4)



## II.3 État de l'art



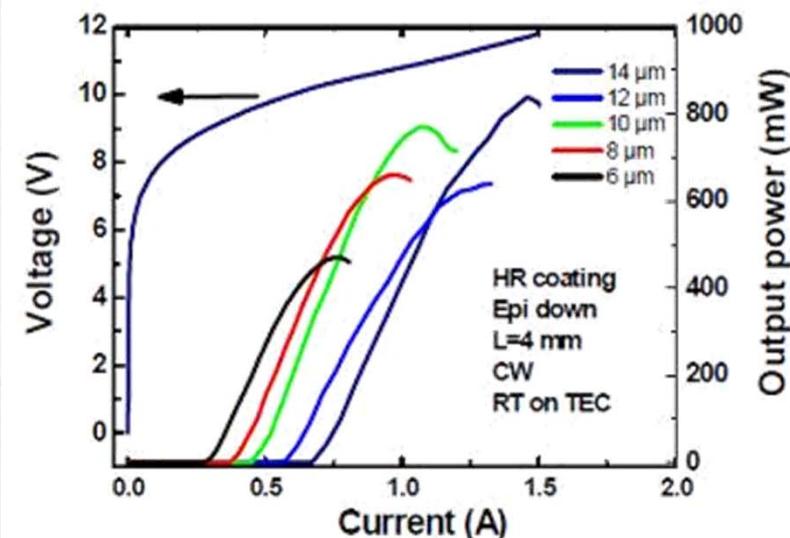
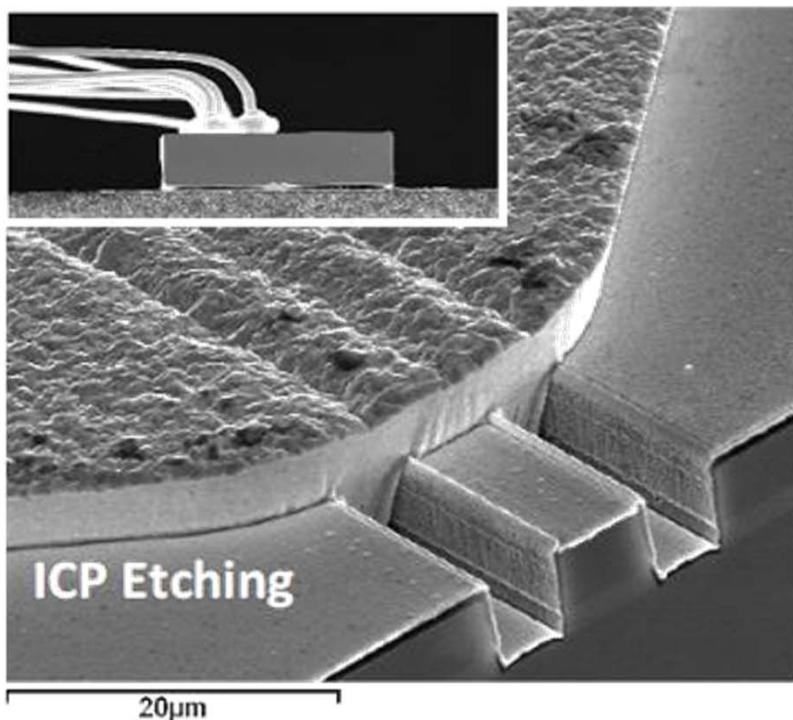
## II.3 QCL: Produits commercialisés

Company name	QCL wafers	QCL sources	QCL systems
AdTech Optics Inc.	X	X	
Aerodyne Research Inc.			X
Alcatel-Thales III-V Lab		X	
Alpes Lasers		X	
Archcom Technology Inc.	X		
Cascade Technologies		X	X
Daylight Solutions Inc.			X
Hamamatsu		X	
IQE	X		
Laser Components Inc.		X	
Maxion Technologies Inc./PSI (Physical Sciences Inc.)	X	X	
Nanoplus Inc.		X	
Neoplas Control Inc.			X
nLIGHT Corporation	X		
Pranalytica Inc.		X	X
QuantaRed Technologies			X
Spire Corporation	X		

R.F. Curl et al. Chem. Phys. Lett. 487 (2010) 1–18

## II.3 Exemples: En France

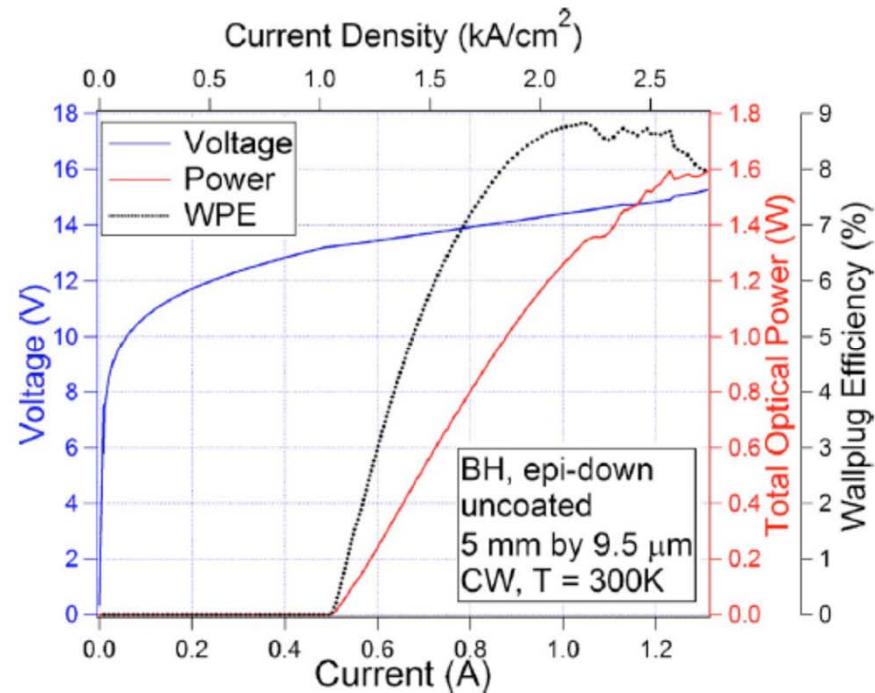
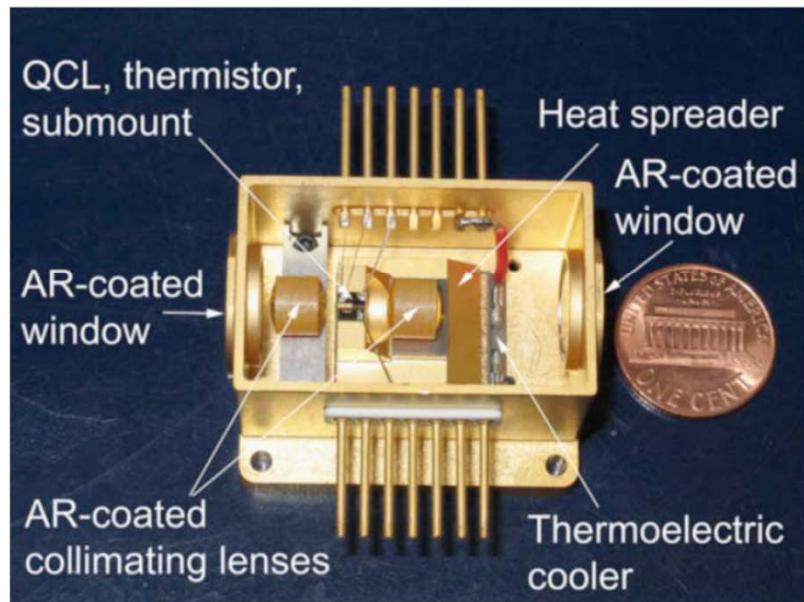
- Au plated, HR coating and epi down mounting



Courtesy of X. Marcadet



## II.3 Exemples: CW

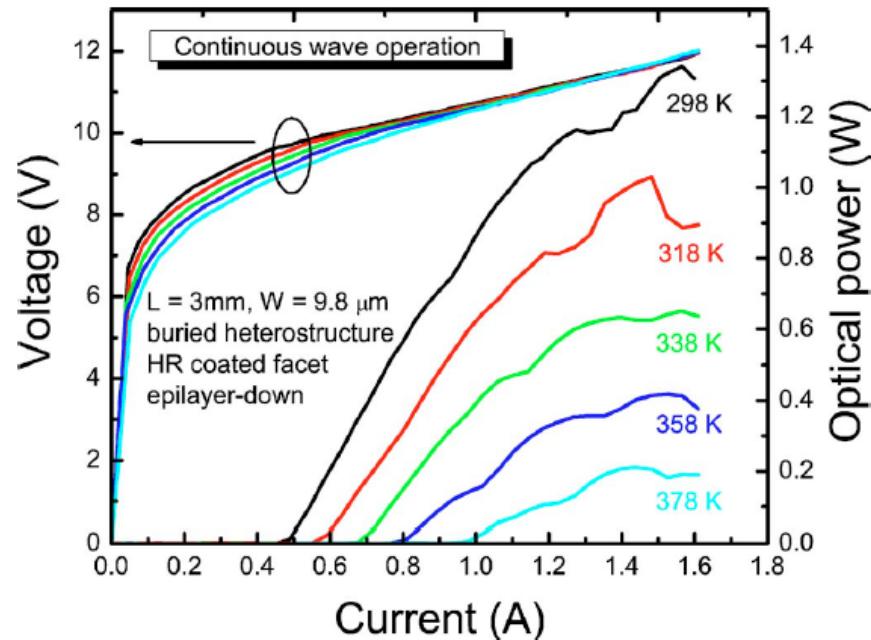
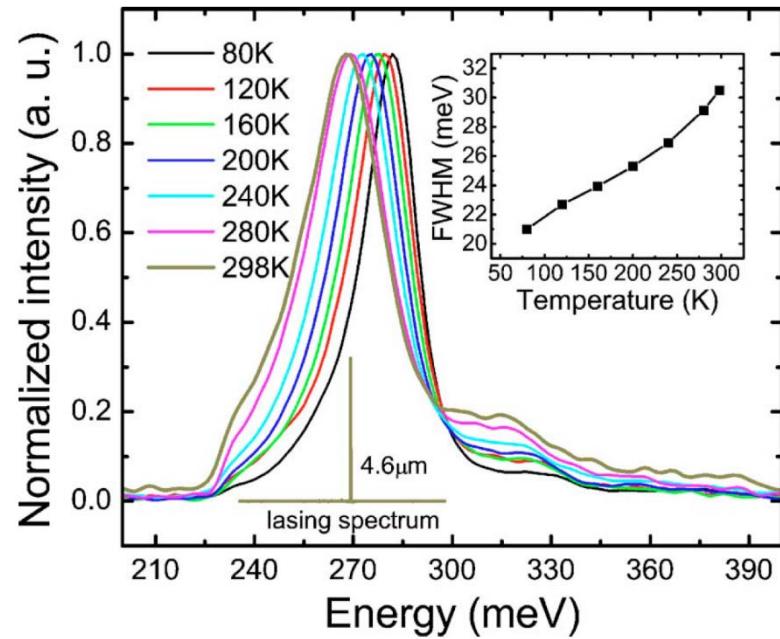


A. Lyakh, et al., APL 92, 111110 (2008)

Division of Engineering and Applied Sciences  
Harvard University



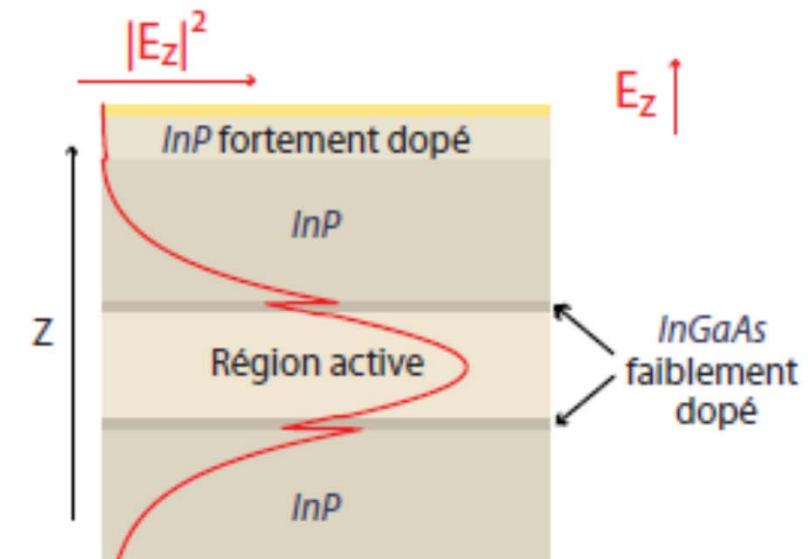
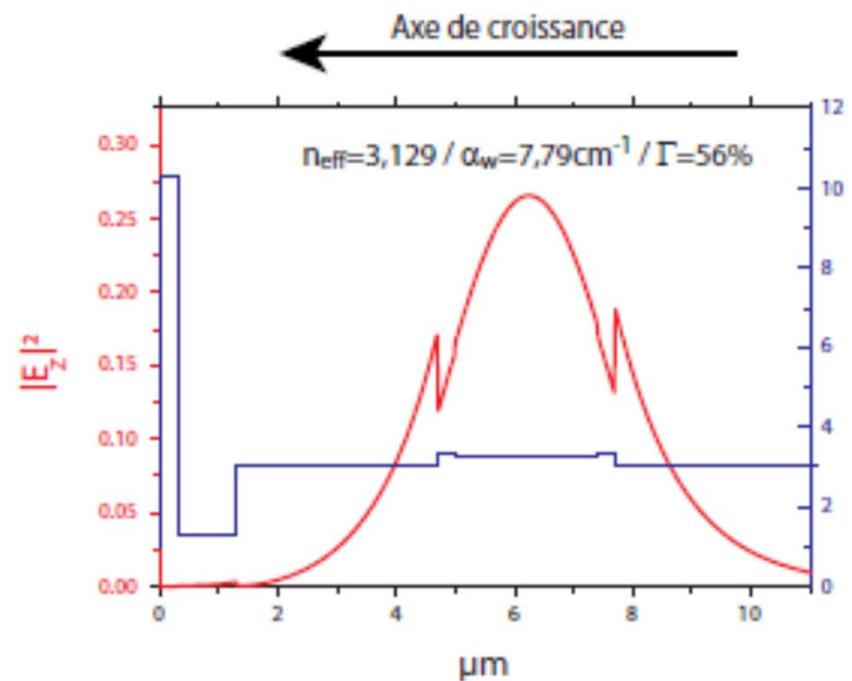
## II.3 Exemples: CW



Y. Bai, et al., APL 92, 101105 (2008)

## II.4.1 Guide optique dans les QCLs

- **Guide diélectrique:**
  - La région active est en « sandwich » entre deux couche de faible indice.
  - La lumière est guidée dans la région active par réflexion totale interne.
  - Facteur de confinement  $\Gamma \sim 0.6$



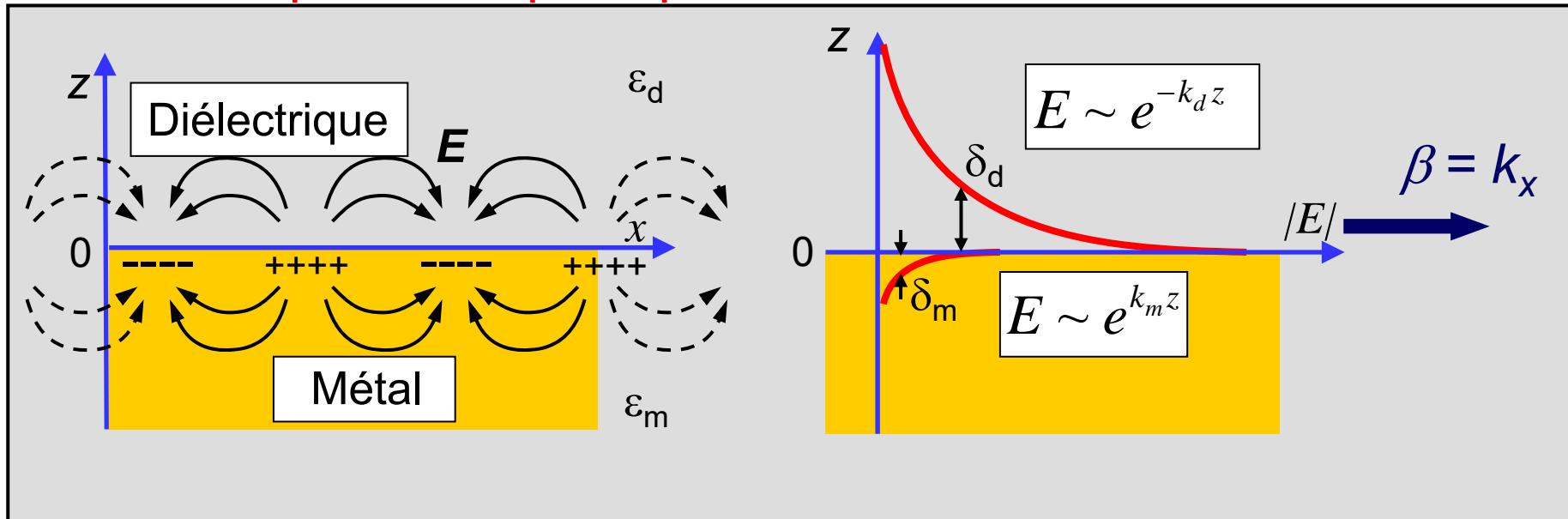
## II.4.1 Guide optique dans les QCLs

---

- **Guide diélectrique: Avantages et limites**
  - Très utilisé dans le système de matériaux InGaAs/AlInAs sur substrat InP. ( $n_{\text{InGaAs}} = 3.4$ ,  $n_{\text{InP}} = 3.1$ ) => très bon contraste.
  - Pas très pratique pour les autres système (GaAs et InAs), où il n'existe pas des matériaux en accord de maille avec le substrat et qui ont un bon contraste avec l'indice de la région active.
  - Pas très pratique aux grandes longueurs d'onde. Il faut des couches de gaine très épaisse pour avoir un bon confinement.

## II.4.1 Guide optique dans les QCLs

- Guides plasmoniques: plasmons de surface?



$$z < 0$$

$$\mathbf{E}(\mathbf{r}) \propto e^{i\beta x} e^{k_m z}$$

$$z > 0$$

$$\mathbf{E}(\mathbf{r}) \propto e^{i\beta x} e^{-k_d z}$$

Interface ( $z$ ) : Onde évanescante ( $k_1, k_2$ )

// Interface ( $x$ ) : Onde propagative ( $\beta$ )

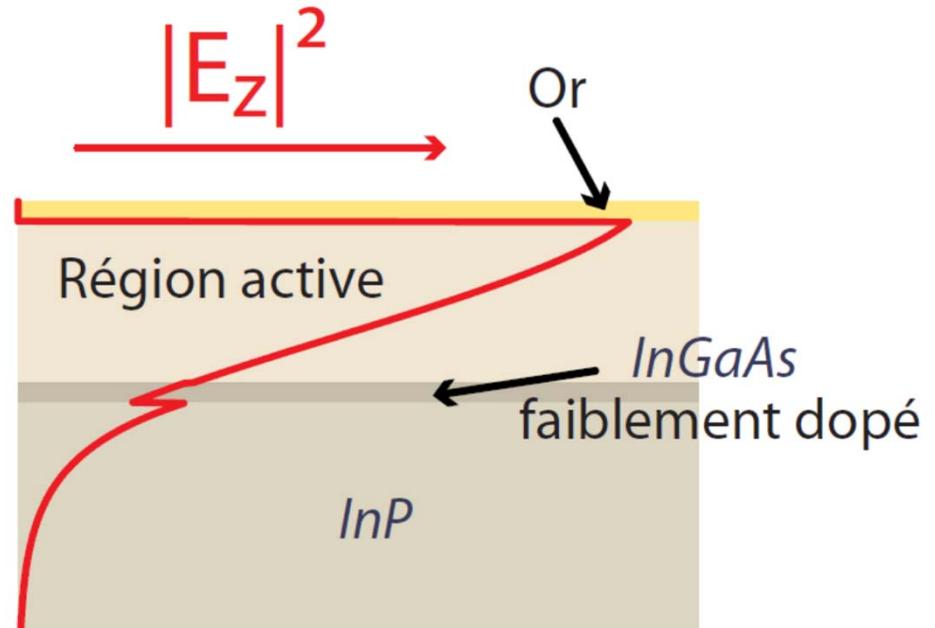
POLARISATION TRANSVERSE MAGNETIQUE (TM)

Un confinement ultime de la lumière dans un espace sub-longueur d'onde

## II.4.1 Guide optique dans les QCLs

- Guides plasmoniques:

- Pertes raisonnable dans le moyen infrarouge
- Facteur de confinement du mode dans la région active  $\Gamma \sim 1$ .
- Encore plus avantageux aux Grandes longueurs d'onde, là où il est difficile de faire des guides diélectrique.
- Pas besoins de matériaux à faible contraste d'indice.
- Pas très avantageux à courte longueur d'onde à cause des pertes.



Métaux	$n_m$	$k_m$	$n_m/k_m^3$	$\alpha (cm^{-1})$
Ag	2,94	54,13	$1,85.10^{-5}$	11,15
Or	4,33	53,84	$2,78.10^{-5}$	16,72
Al	18,96	82,50	$3,38.10^{-5}$	20,33
Ni	4,84	27,70	$2,27.10^{-4}$	137,1
Pd	4,40	16,25	$1,10.10^{-3}$	617,4
Ti	6,31	13,90	$2,30.10^{-3}$	1414

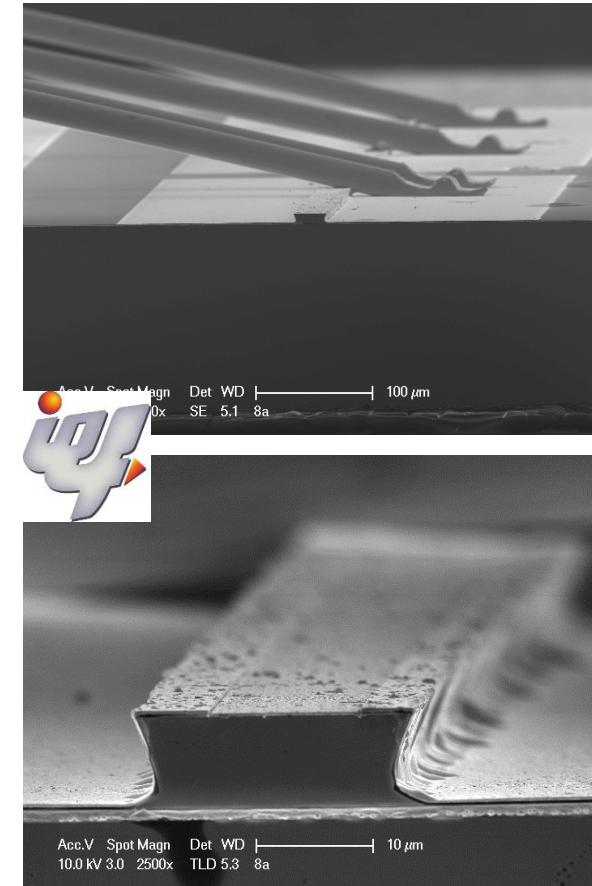
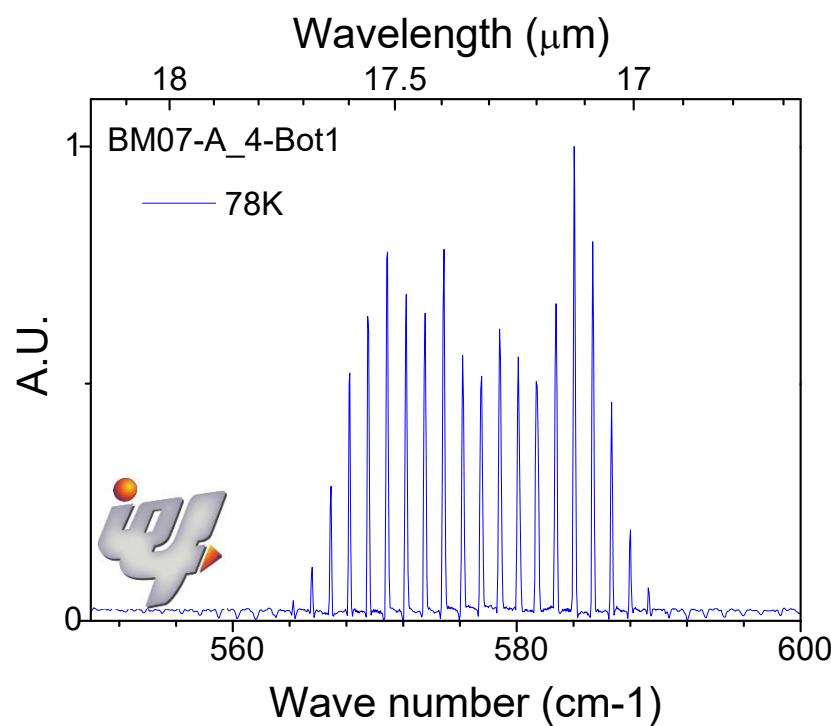
## II.4.3 Contrôle de modes

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- Il existe différents types de cavité optique:
  - Guide Fabry-Pérot: Les miroirs de la cavité optique sont formés par les deux facettes clivées du ruban. La réflectivité est de l'ordre de 30% (sans traitement HR). Les modes longitudinaux ne sont pas contrôlés. L'émission ne peut être stabilisée sur un seul mode.
  - Guide DFB: L'introduction d'une légère modulation de l'indice de réfraction le long du guide permet la sélection d'un mode longitudinal. Il correspond à la fenêtre de transparence du filtre de Bragg ainsi obtenu.
  - Cavité externe : Un laser Fabry-Pérot (avec un dépôt anti-réflexion sur une facette) est envoyé sur un réseau de diffraction et est réinjecté dans la cavité. Un seul mode est sélectionné.
  - Laser à émission par la surface: Périodicité (2D), condition de Bragg au 2<sup>ième</sup> ordre=> émission par la surface.

## II.4.3 Contrôle de modes

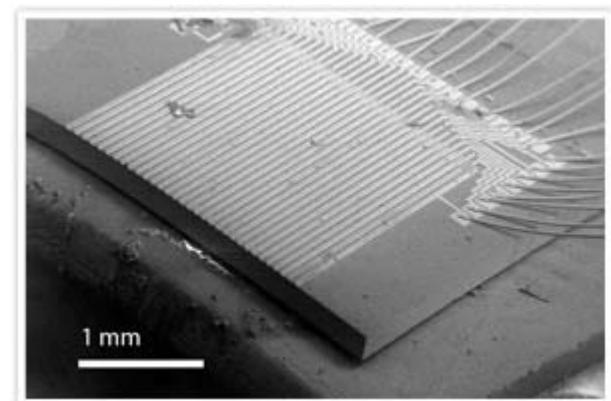
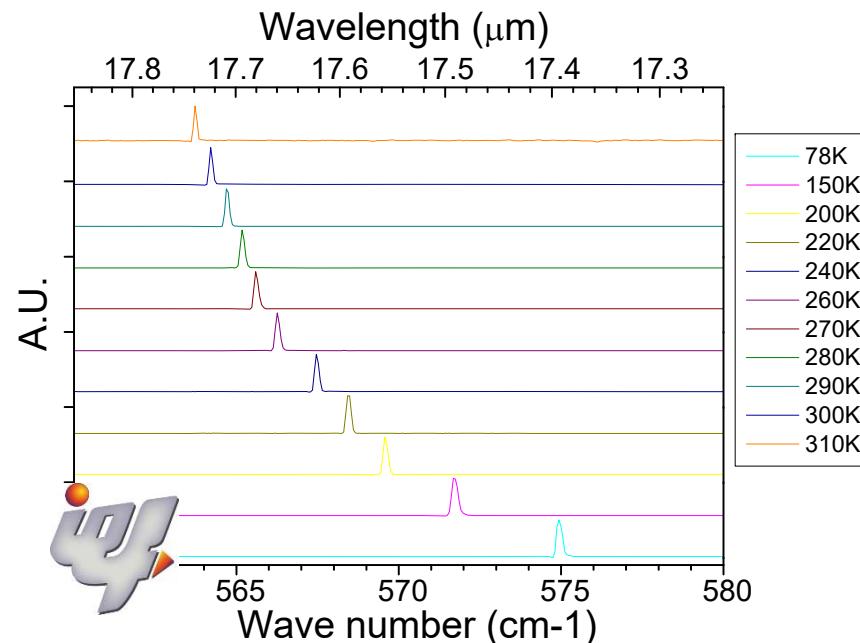
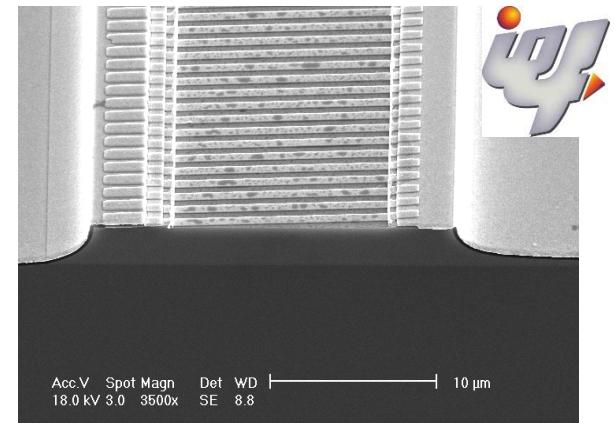
- **Cavité Fabry Pérot:**
  - Émission multi mode longitudinal.
  - En CW il est impossible de contrôler la position de la raie d'émission.
  - Espacement entre les modes: ISL, dépend de la longueur de la cavité.



## II.4.3 Contrôle de modes

- **Cavité DFB:**

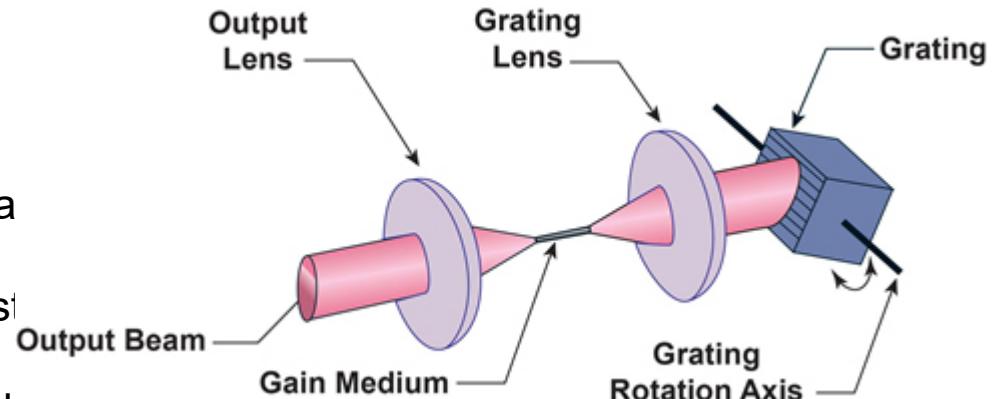
- La longueur d'onde est fixée par la période du réseau.
- L'accordabilité peut être obtenue en ajustant la période.
  - Sur le même dispositif: changer la température. couverture de qlq  $\text{cm}^{-1}$
  - Avec des dispositifs adjacents qui ont des périodes différentes => accordabilité sur une plage plus grande.



## II.4.3 Contrôle de modes

- **Cavité Externe:**

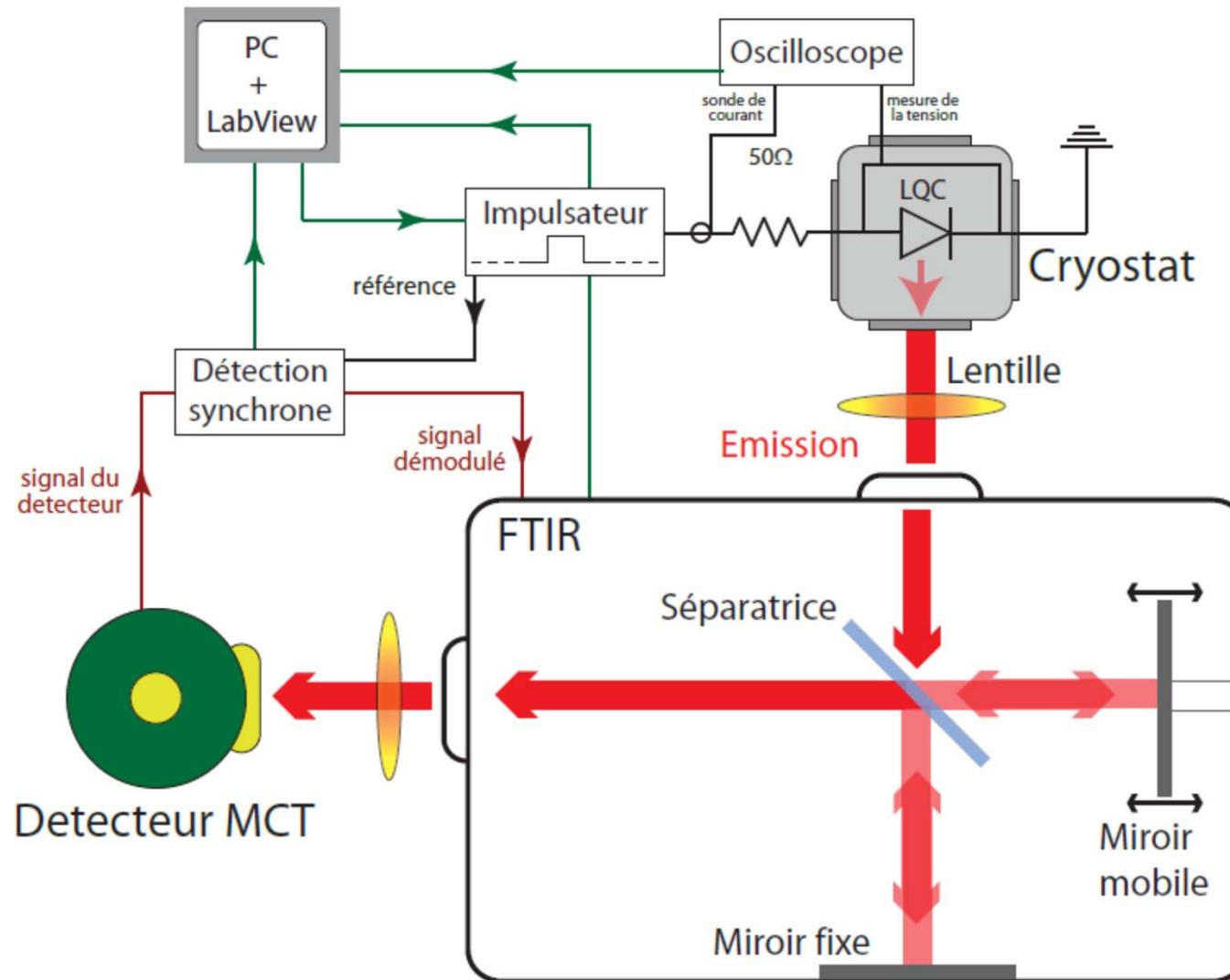
- Un laser Fabry-Pérot (avec un dépôt anti réflexion sur une facette) est envoyé sur un réseau de diffraction et est réinjecter dans la cavité. Un seul mode est sélectionné.
- Accordabilité sur une centaine de  $\text{cm}^{-1}$ !
- Sensibilité aux bruits mécanique
- Complexité du système.



- **Exemple:**

- Daylight slotion
- Large gamme d'accordabilité:  $800\text{cm}^{-1}$
- Mode pulsé est continu
- Puissance de qlq centaines de mW.
- Couvre la gamme  $4\text{-}12\mu\text{m}$
- Coût: 70k Euros!

## II.4.4 Caractérisation: Optique et électrique



## II.4.4 Caractérisation: Divergence

