Chapter 3
Inorganic nanostructures in telecommunications

3.1 transparent conducting oxide electrodes (TCO)
3.2 electrochromy
3.3 electroluminescence (OLED, nano-based LED)
3.4 planar waveguides and NIR amplifiers in photonic circuits

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3.1 *transparent conducting oxides TCOs*

Introduction

Figure of merit ~ T/R

$$t\,R = \rho = 1 / e\,N\,\mu$$

R: lateral resistivity
ρ: resistivity
N: free carrier concentration
μ: carrier mobility
t: thickness
e: elementary charge
T: optical transmission

Desired parameters:

T (400-1200 nm) > 80%
$E_g > 3$ eV
N ~ 10^{20} - 10^{21} cm^{-3}
μ > 100 $cm^2\,V^{-1}\,s^{-1}$
t ~ 500 nm - 1 μm
ρ < 10^{-4} Ω cm
R < 2 Ω $sq.^{-1}$ (t = 500 nm)

Application domaines:

Photovoltaics (CdTe, Si, CIGS)
Telecommunication
(LCD, OLED, electrochromy)

Smart windows

Transparent conductors as solar energy materials: A panoramic review

Claes G. Granqvist*

Solar Energy Materials & Solar Cells 91 (2007) 1529–1598

1. Control of N: doping!
2. Control of μ: morphology!
3. Optical gap : oxides!

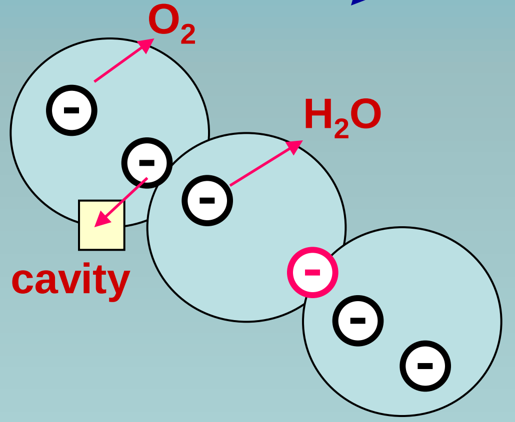
TCO n-doped

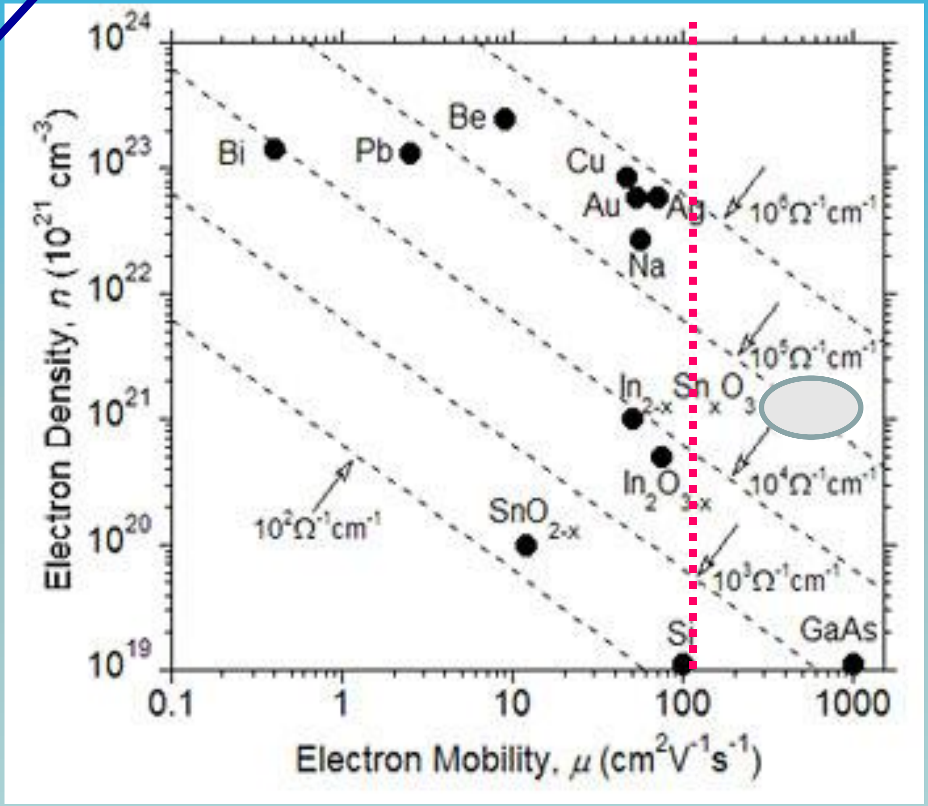
$ITO : In^{3+}_{2-x}Sn^{4+}_{x}O_{3}e^{-}_{x}$

$ATO : Sn^{4+}_{1-x}Sb^{5+}_{x}O_{2}e^{-}_{x}$

$FTO : Sn^{4+}O_{2-x}F^{-}_{x}e^{-}_{x}$

$AZO : Zn^{2+}_{1-x}Al^{3+}_{x}Oe^{-}_{x}$





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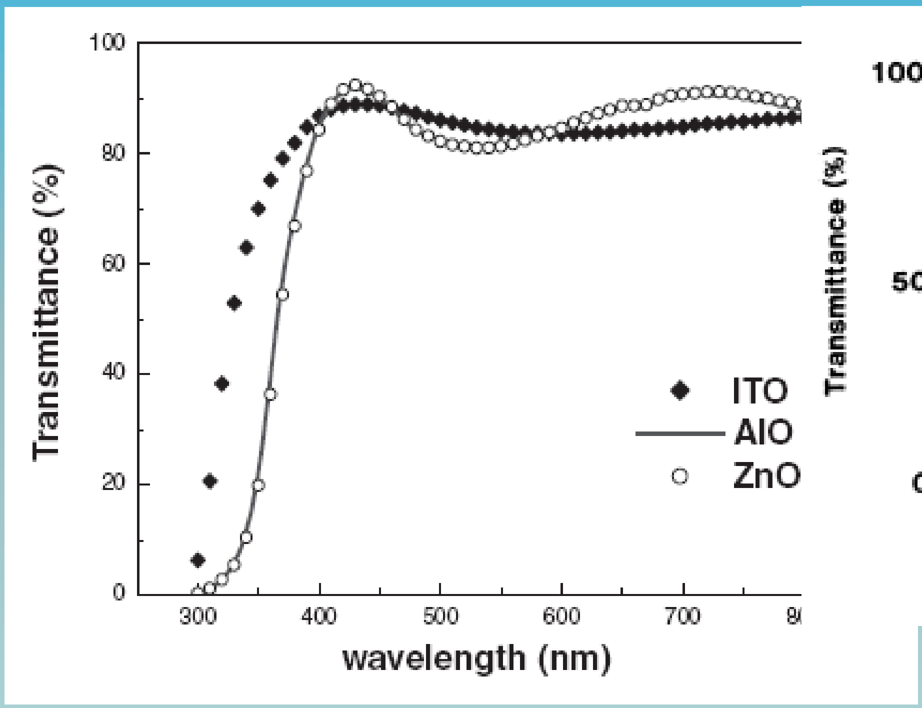
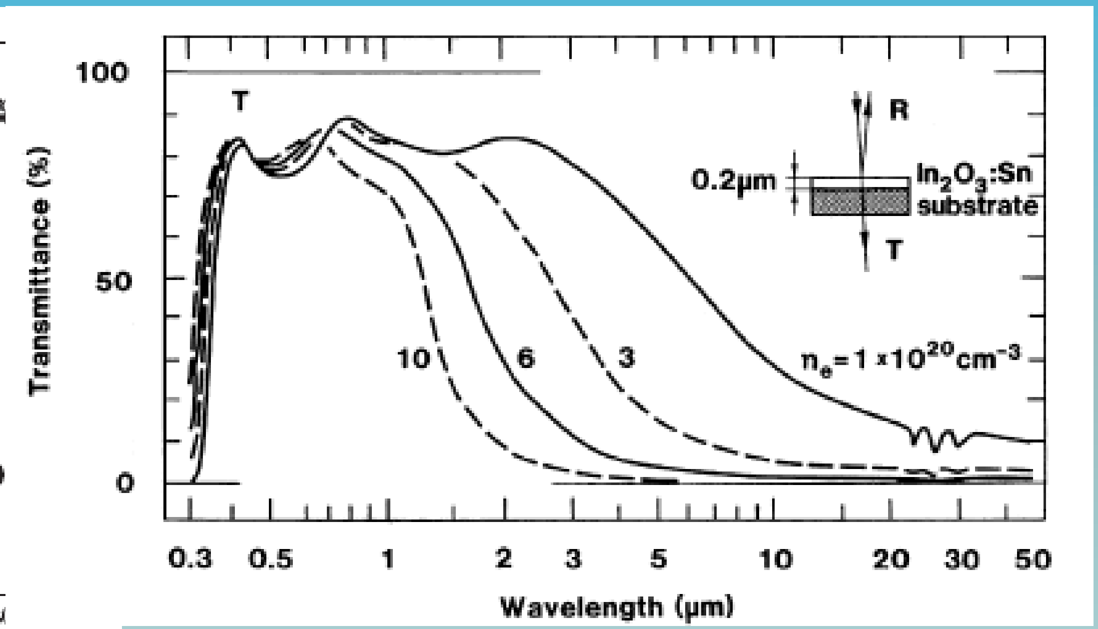
Profile spectrale de transmission optique





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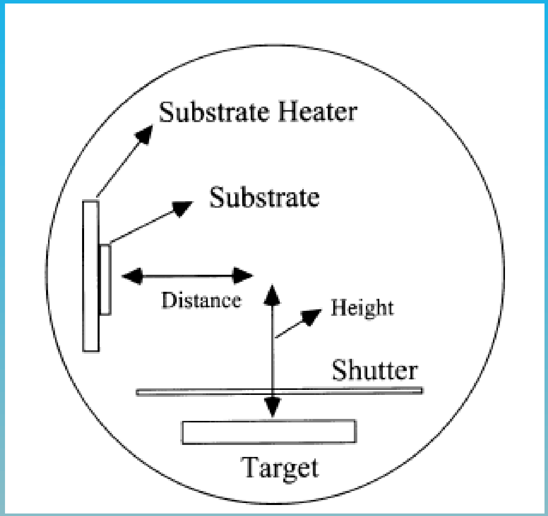
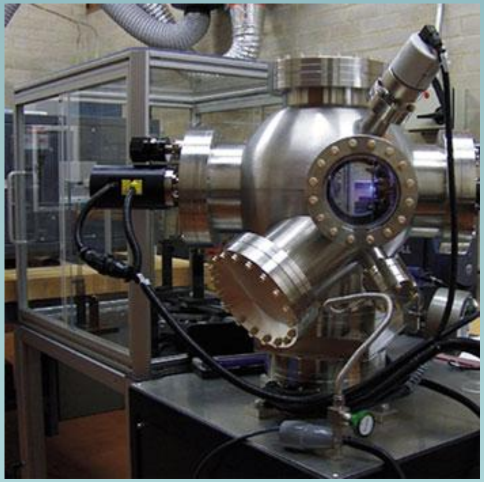
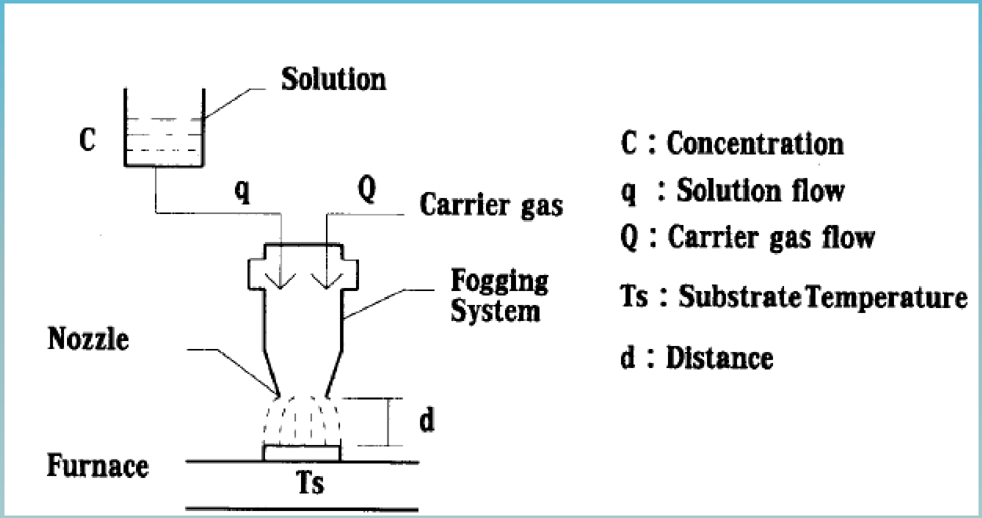
Elaboration of thin film electrodes



Pulsed Laser Deposition

Rf-magnetron sputtering





Chemical spray

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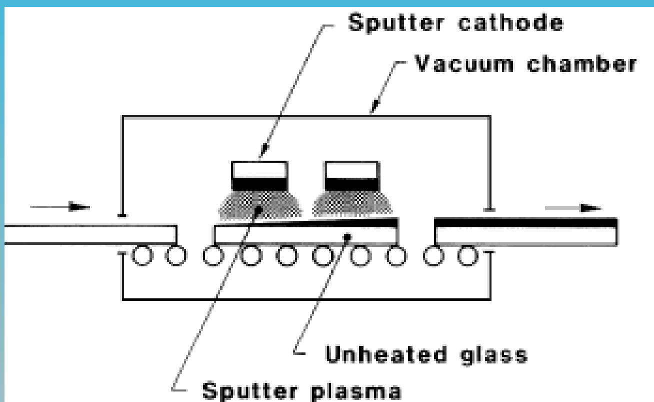
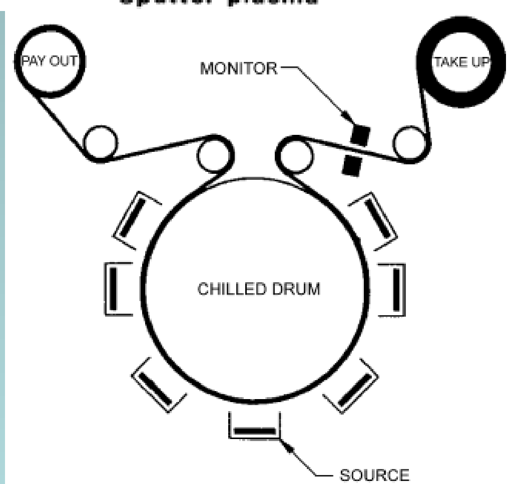
Contineous Elaboration of TCO

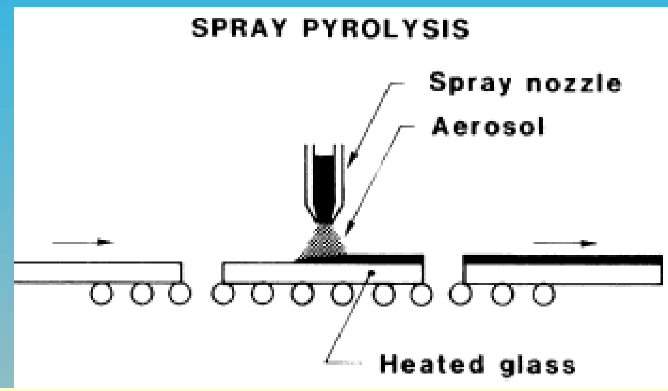
Pulsed Laser Deposition

Sputtering



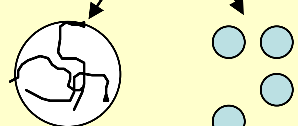


Spray pyrolysis



Chimie douce

molécule alcoxylée —H&C→ Sol —dip/spin→ Gel —recuit→ Films



polymérique particulaire

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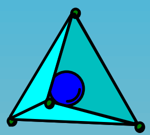
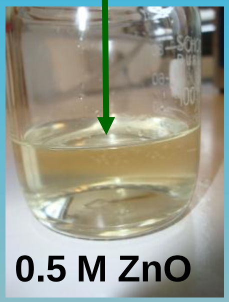


TMA-OH

90°C

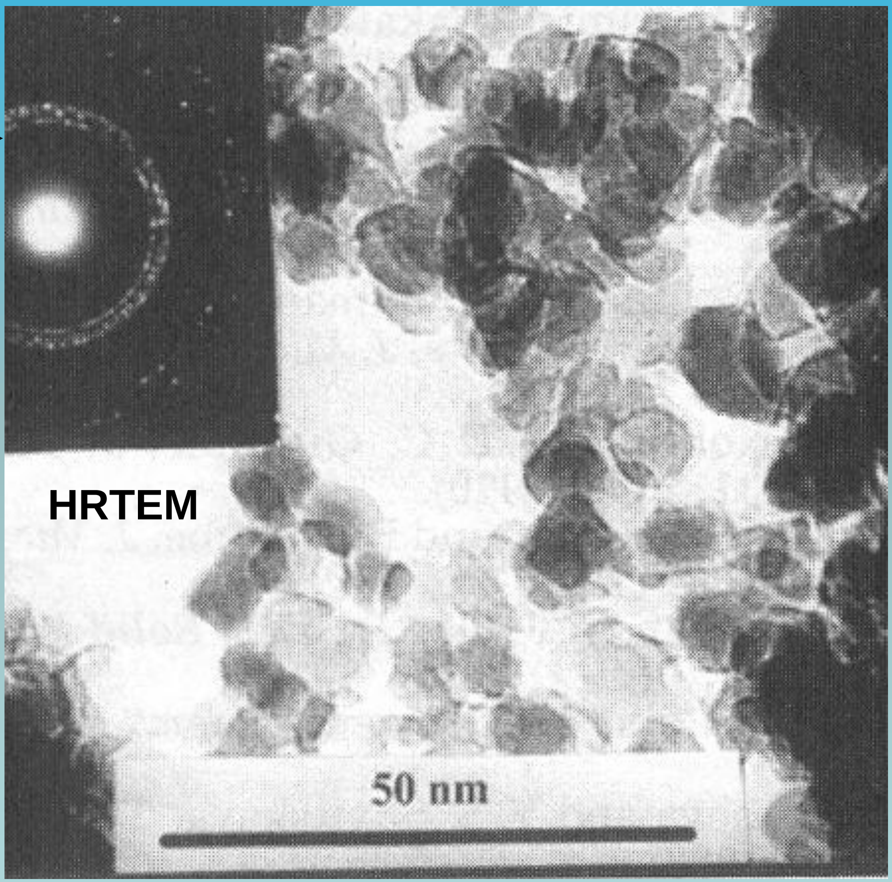
$Al-(OC_4H_9)_3$

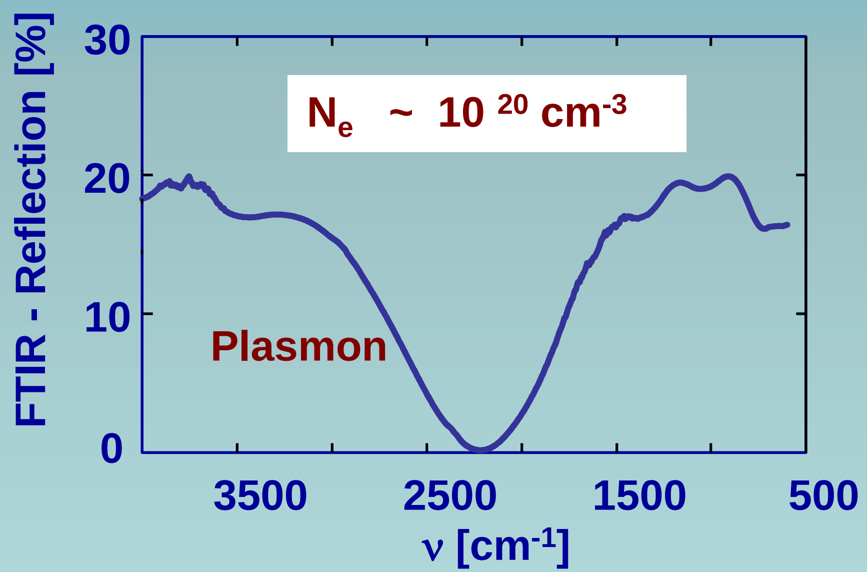


Dip coating

N_2/H_2 - sintering

$\mu_e < 10^{-3}\ cm^2 / V\ s$





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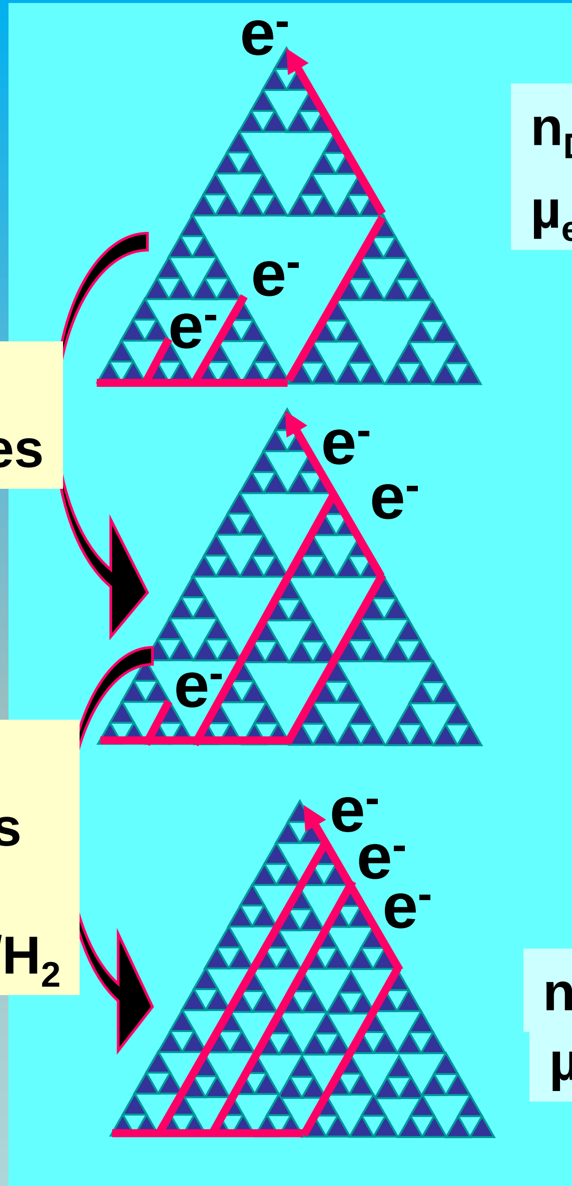
condensation dans mesopores

Infiltration des mesopores & recuit sous N_2/H_2

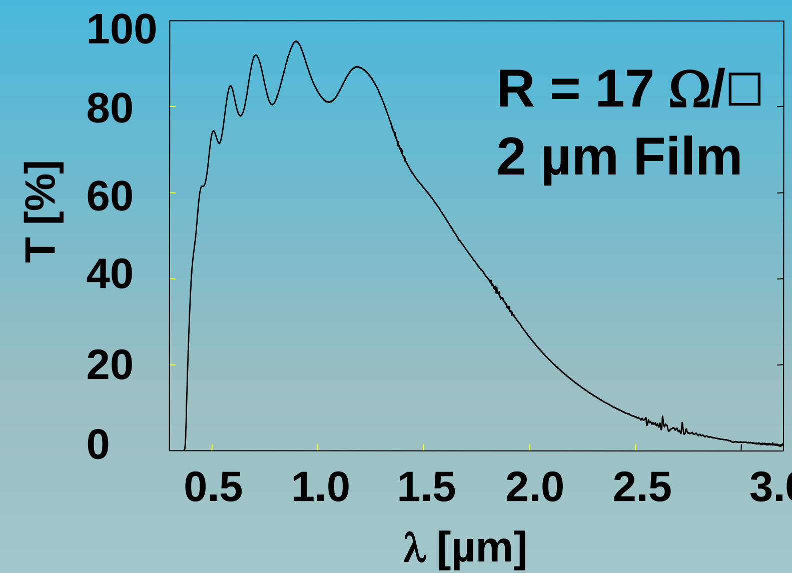


$n_D \sim 1.7$

$\mu_e = 0.001\ cm^2/Vs$

$n_D \sim 2.1$

$\mu_e = 9\ cm^2/Vs$



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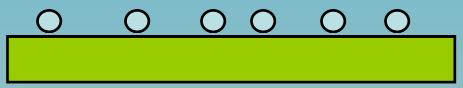
ISAM = “ionic self-assembled monolayer”, Chem. Phys. Lett. 1998, 298, 315

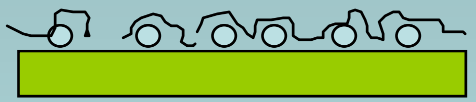
$HAuCl_4/NaBH_4/H_2O/PDDA$

Sol: Au:PDDA
size: 3-6 nm

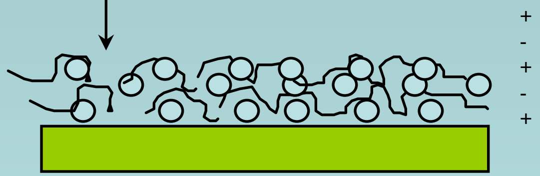
Spin-on



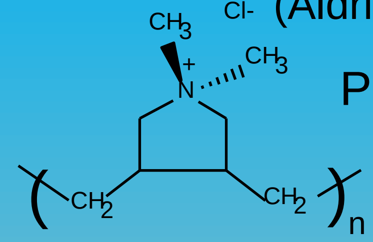
washing &
deposition of Poly s-119



12 times repeated coatings

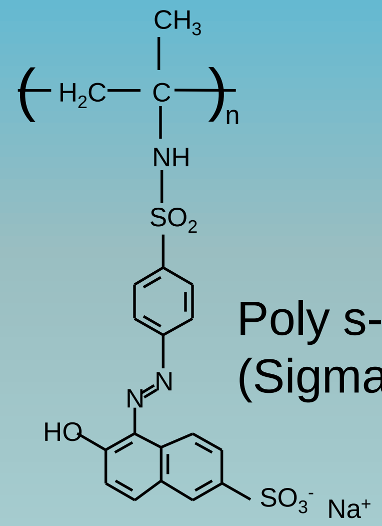


thickness : 50 nm
R = 10^{-6} Ω cm



(Aldrich)

PDDA



Poly s-119
(Sigma)

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3.2 Chromatic materials

Principle of chromaticism

Initial state uncolored ⟷ **reversible** ⟷ **Colored state**

ΔT : thermochromy

$\vec{E}$: electrochromy

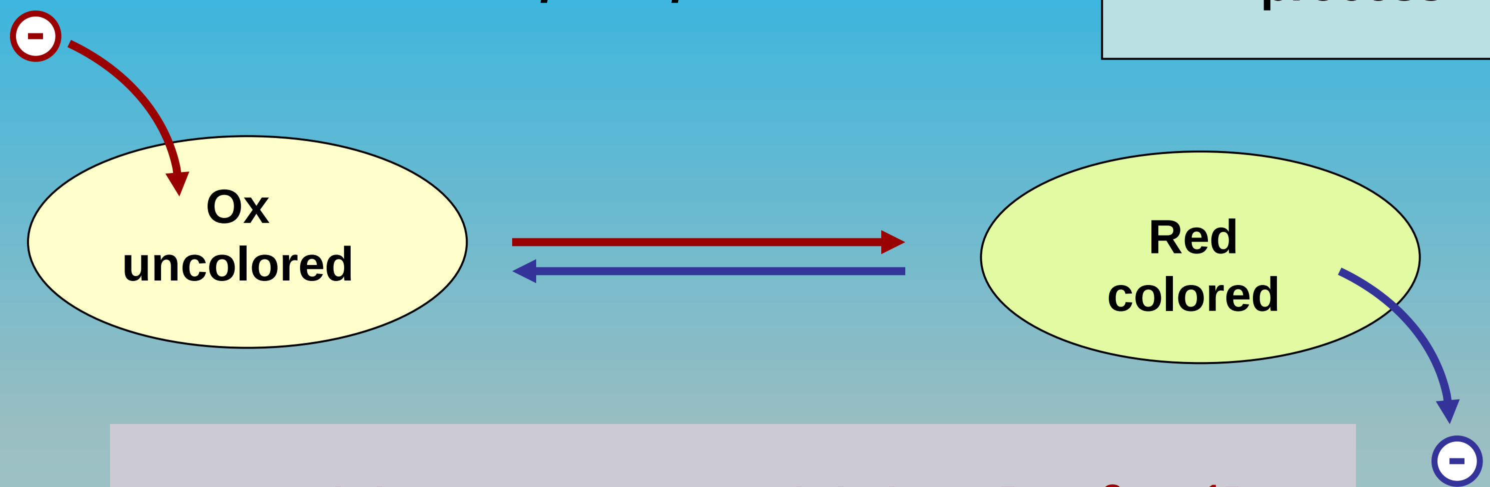
$h\nu$: photochromy

H_2/O_2: gasochromy

Electrochromy

Basic principle

Coloration in reversible redox process



$$CE\ (\lambda) = \eta = \Delta\ O.D.\ (\lambda)\ /\ Q \quad [cm^2\ C^{-1}]$$

CE = coloration efficiency
O.D. = optical density
Q = charge transfered per cm^2

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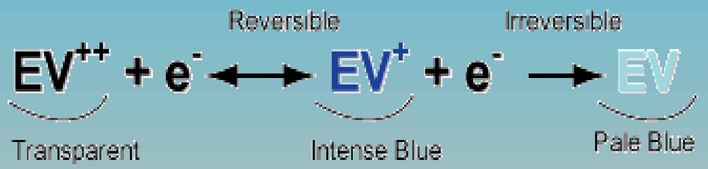
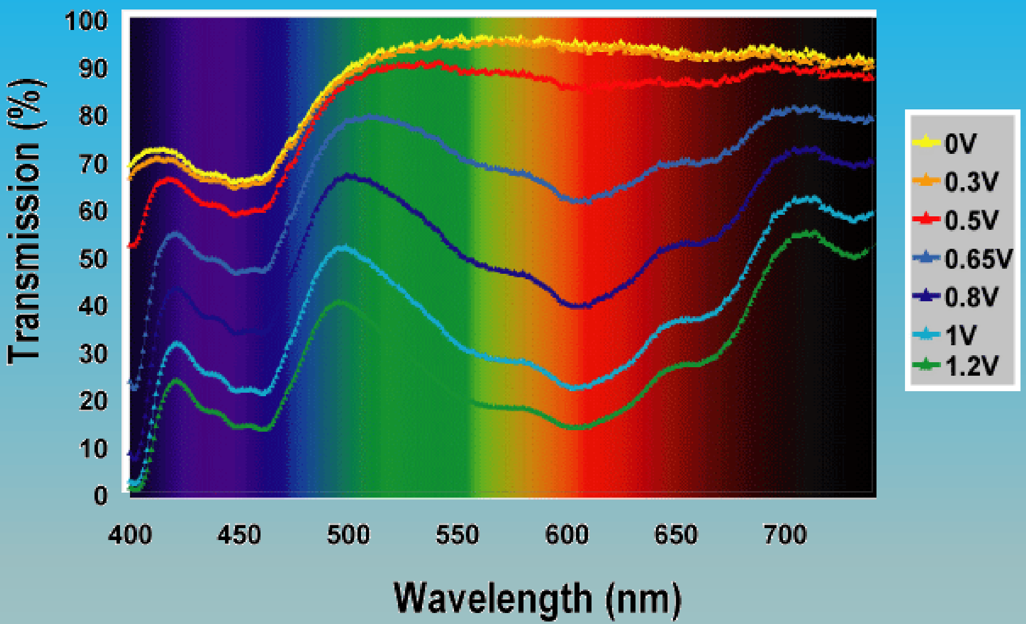
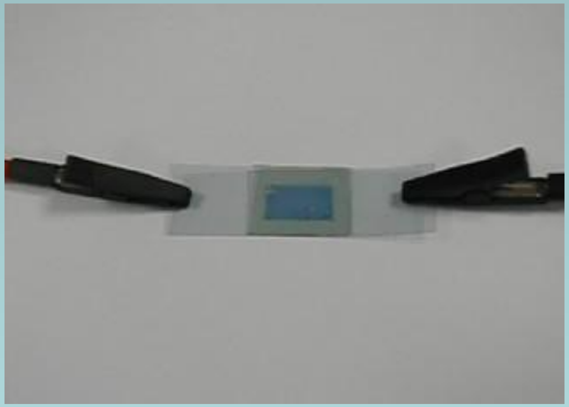
Alkyl-viologenes (methyl-, ethyl-)







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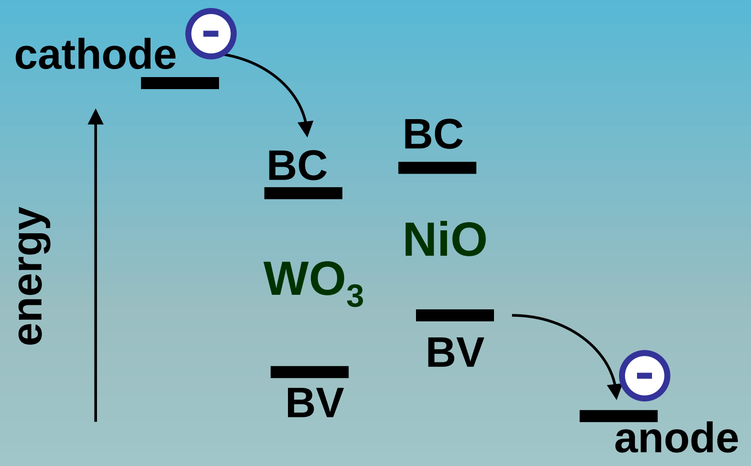
Catodic Coloration:

WO_3, MoO_3, V_2O_5, Nb_2O_5, TiO_2, Cu_2O

colored

$WO_3 + ne^- + n\,M^+ \leftrightarrow M_nWO_3$

W^{6+}-O^{2-}-W^{6+} $\quad$ W^{6+}-O^{2-}-H^+(W^{5+})



Anodic Coloration:

NiO, CoO, Cu_2O, IrO_2

colored

$Ni(OH)_2 \leftrightarrow NiOOH + H^+ + e^-$

$NiO + Ni(OH)_2 \leftrightarrow Ni_2O_3 + 2H^+ + 2\,e^-$

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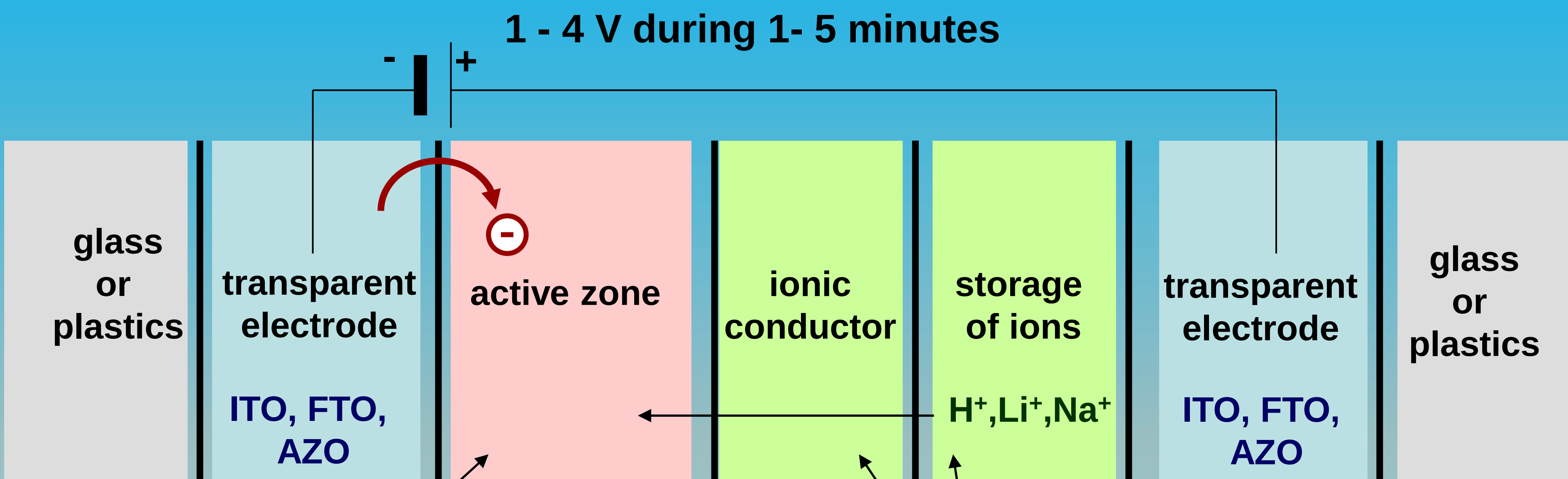
Electrochromic cells



molecules
nanoparticles
org. polymers

Good conductor
(ionic/electronic!)
Life time: 10.000 - 100.000 cycles
(5-20 years)

Ionic conductors

Gels, membranes:
- ZrO_2, Ta_2O_5
- organosiloxanes
- org. polymers: PEO, PVA

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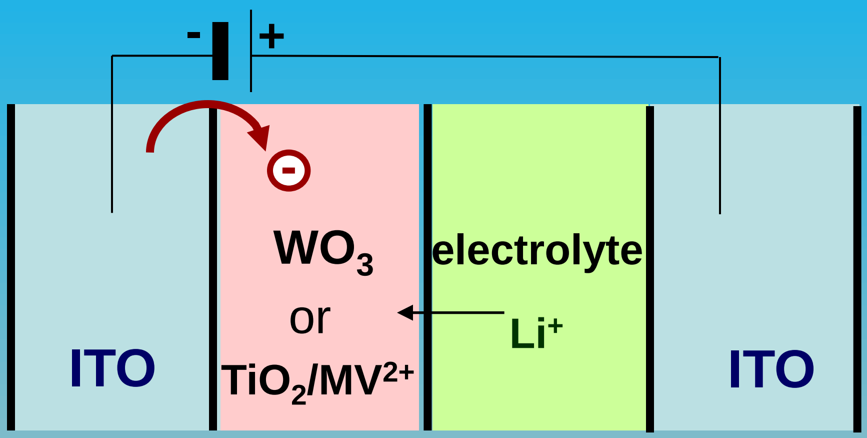
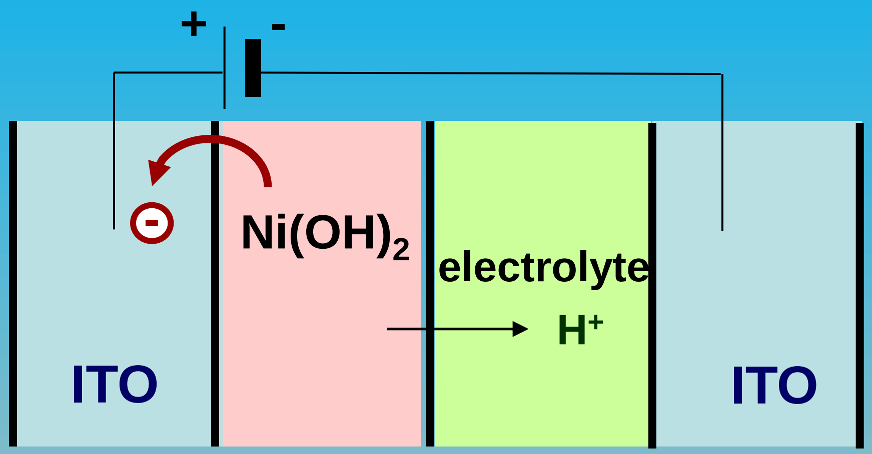
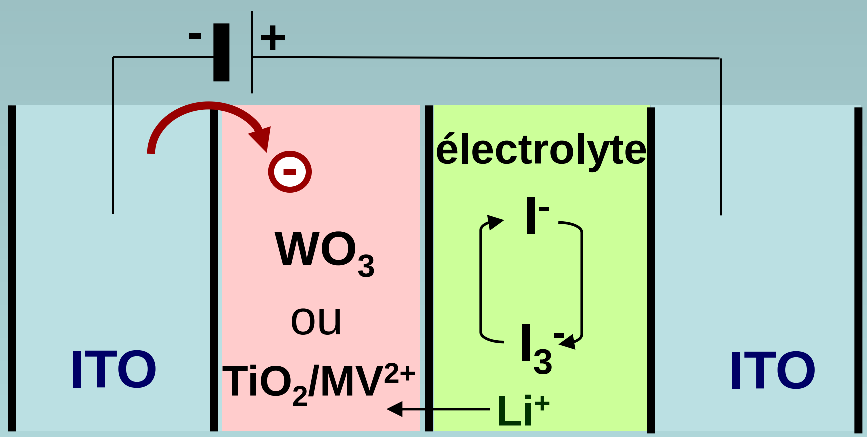
Catodic Coloration



Anodic Coloration



Catodic Coloration with propulsion



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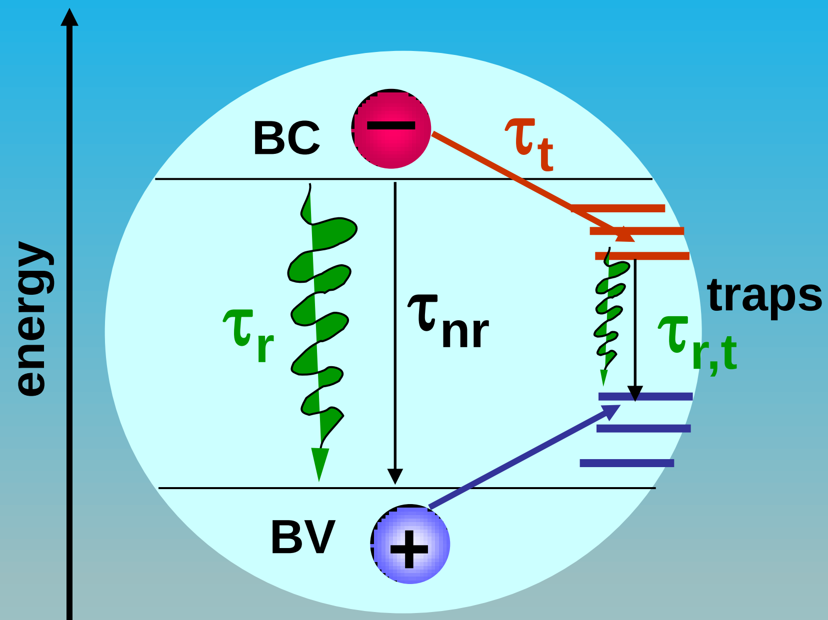
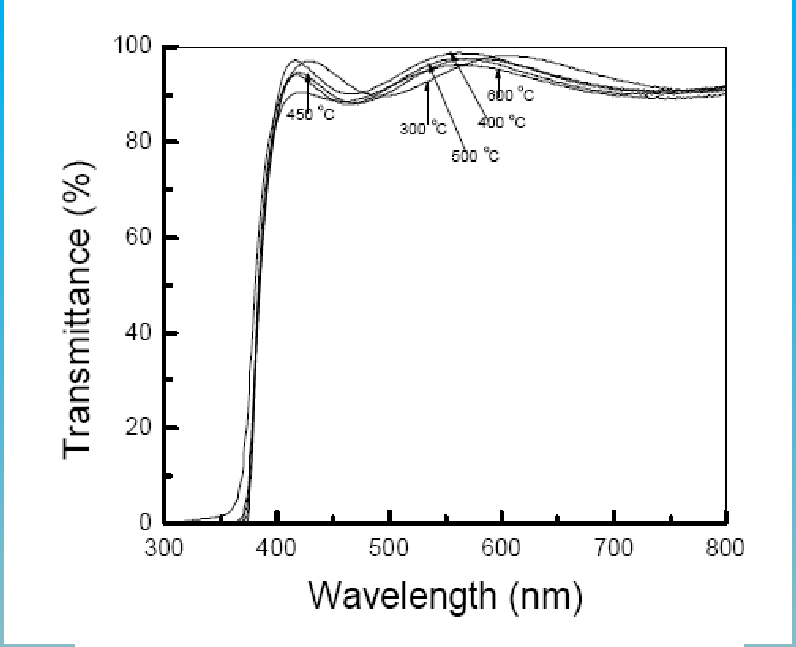
Pilkington, St Gobain, Daimler Chrysler

3.3 Photo- and electroluminescence of semiconductor nanoparticles

Application domains:

1. Bio-imaging systems
2. Electroluminescence (displays)
3. Photonic circuits: amplifiers (LASER)

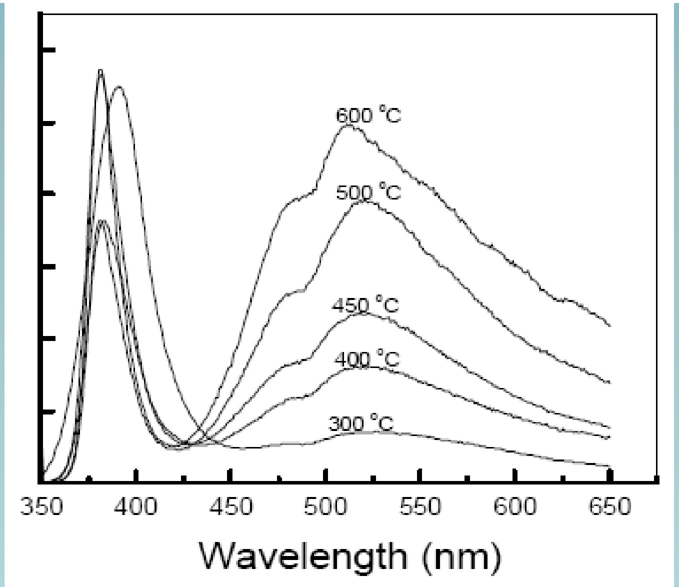




$$\tau_t \sim \tau_D \sim \tau_{nr}$$

$$\tau_{r,t} > \tau_r > \tau_{nr}$$

$\Phi < 0{,}1\%$



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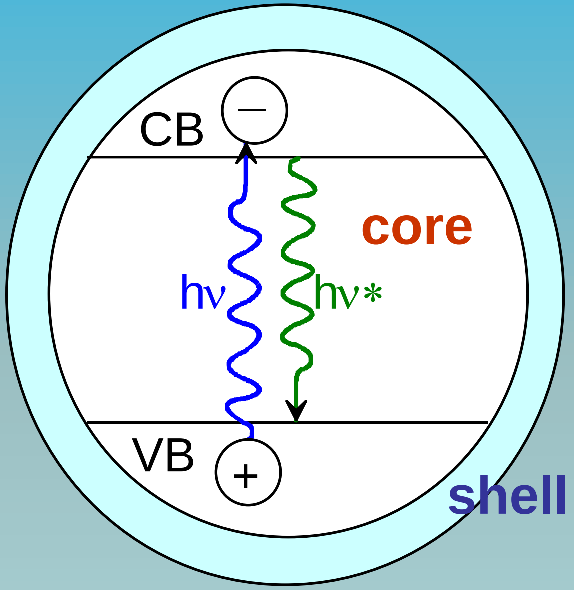
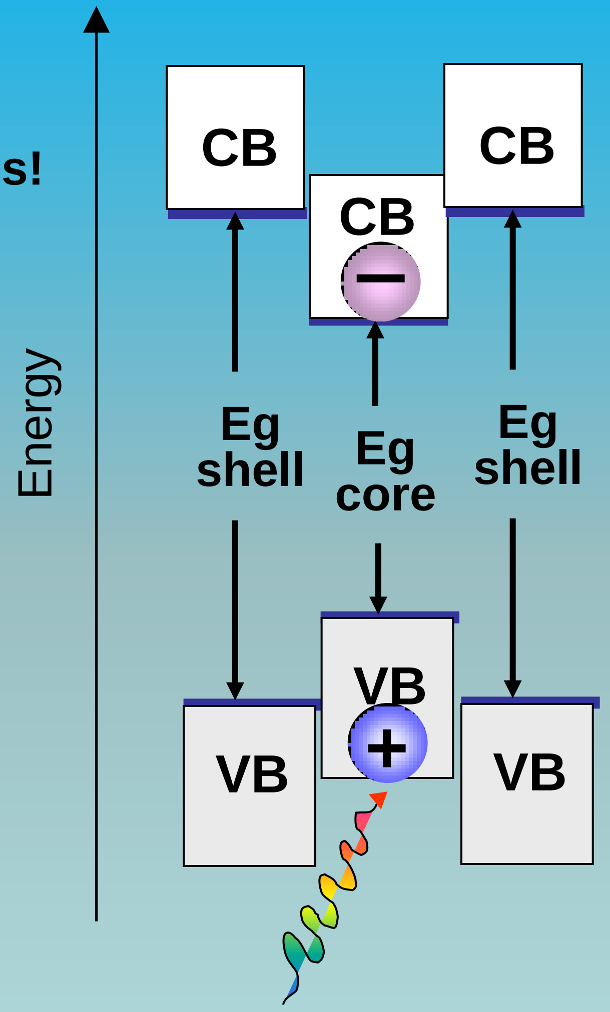
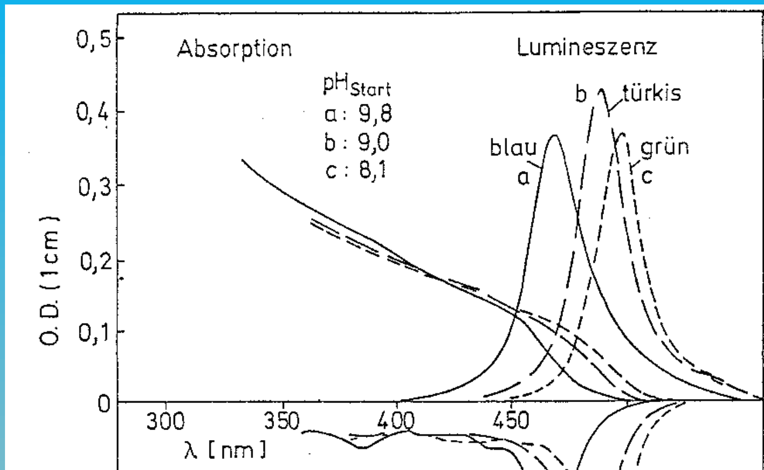
"core/shell" nanostructures

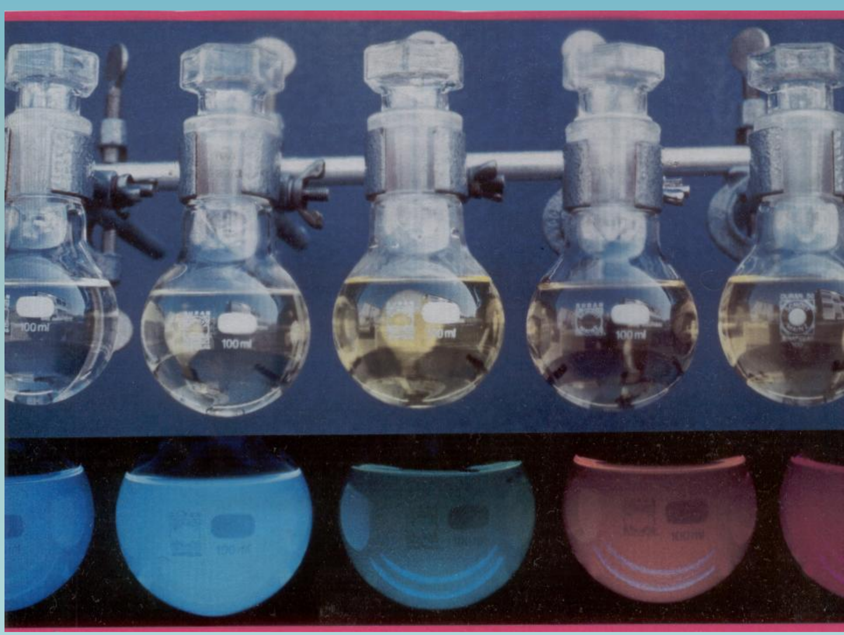
Surface passivation, elimination of traps!



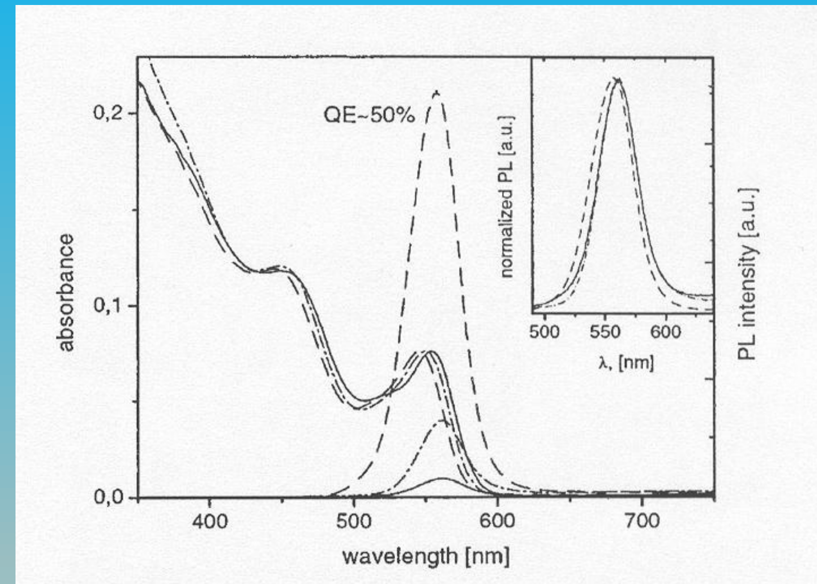


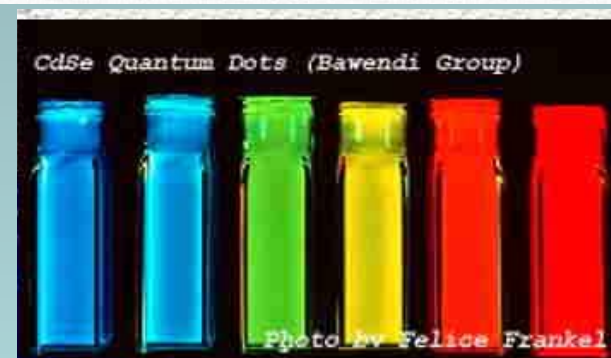
$CdS\text{-}Cd(OH)_2$





CdSe-ZnS





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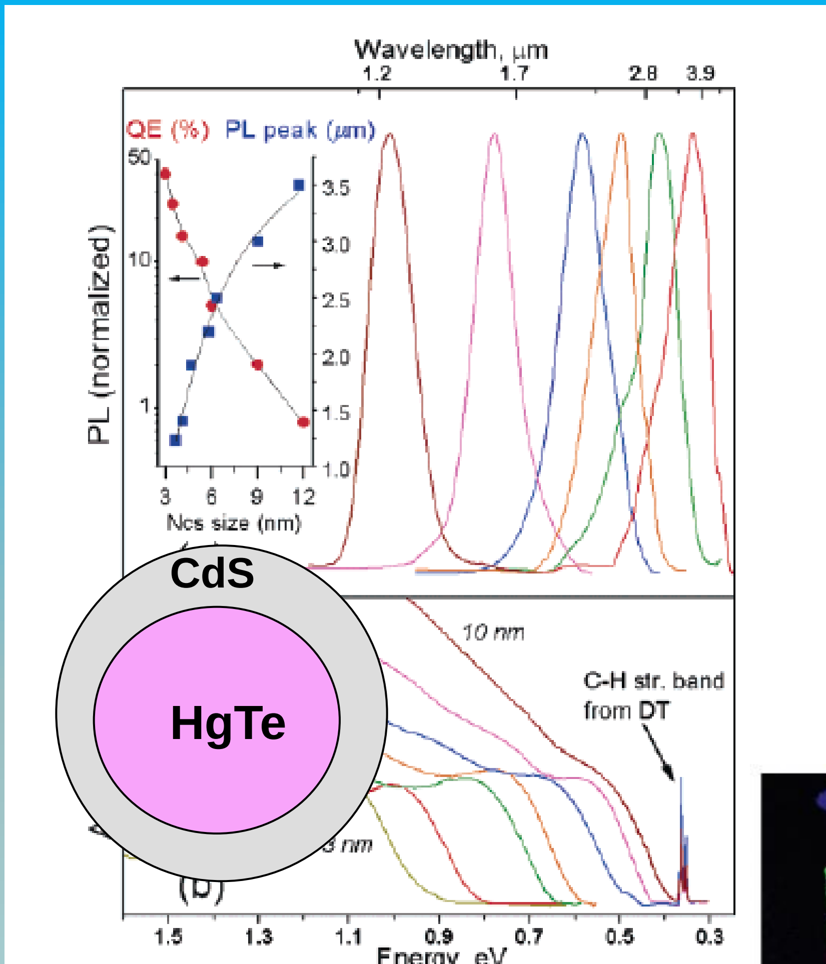
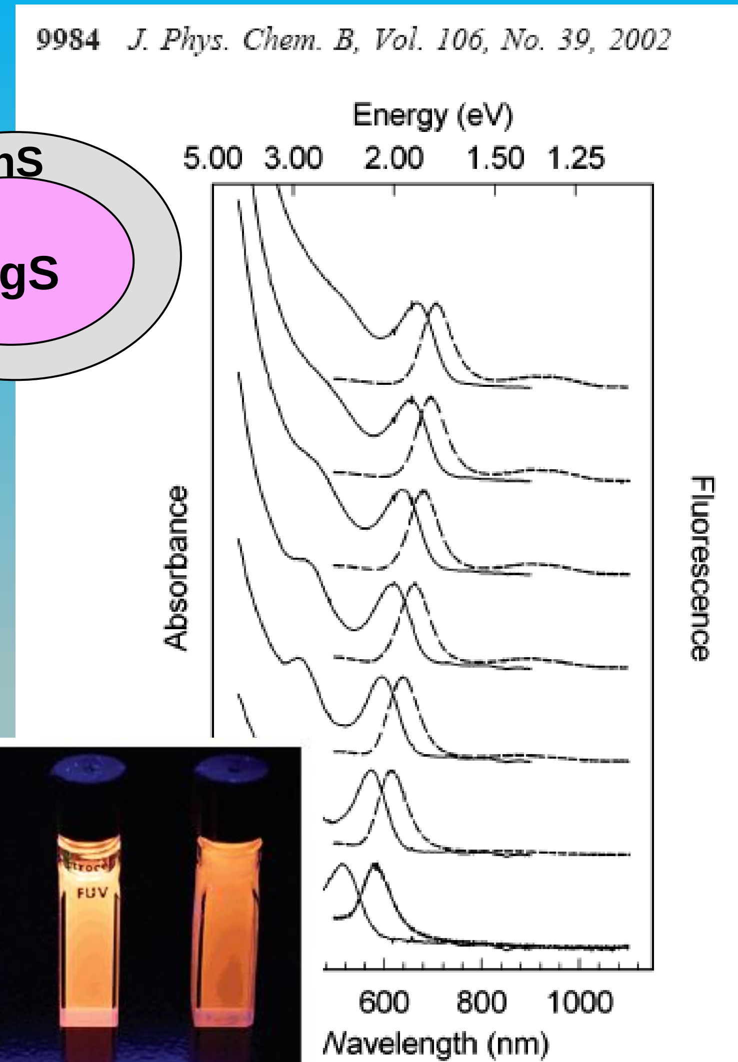
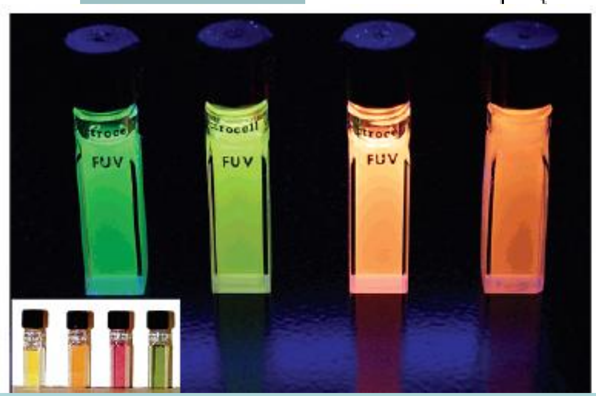


Figure 1. Representative room temperature PL (a) and absorptio spectra of DT-capped HgTe NCs in CCl_4. The insets show th dependence of the PL peaks with the corresponding quantum effici (a) and illustrate the phase transfer completeness for MEA used as stabilizer (b).





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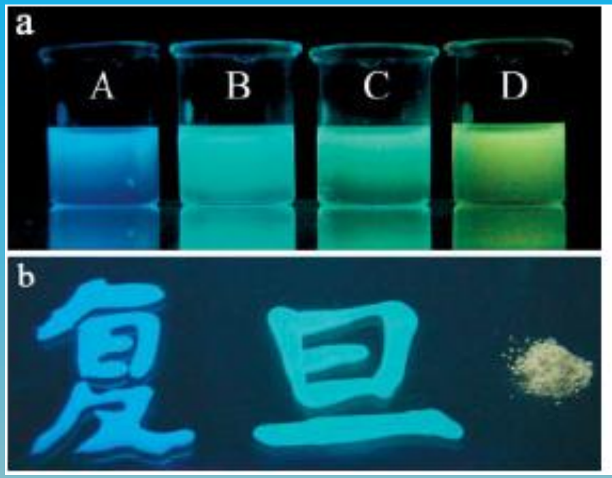
PEG-ZnO nanocomposites

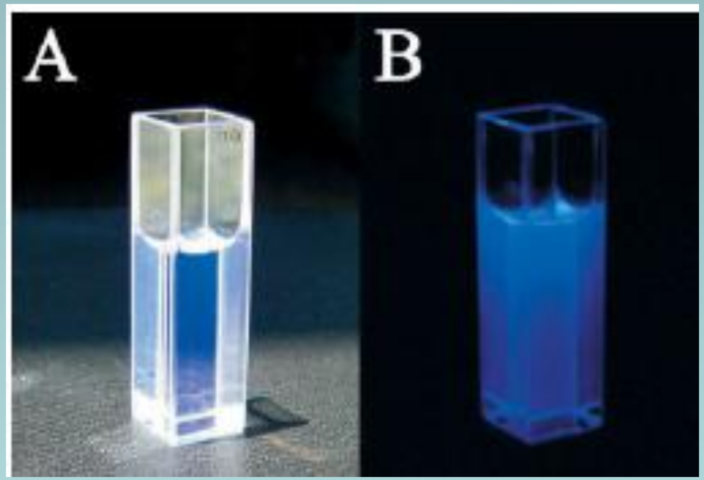


H.M. Xiong et al
Adv. Funct. Mater. 2005
Adv. Mater. 2006

Li-ZnO-SiO_2 „core-shell“

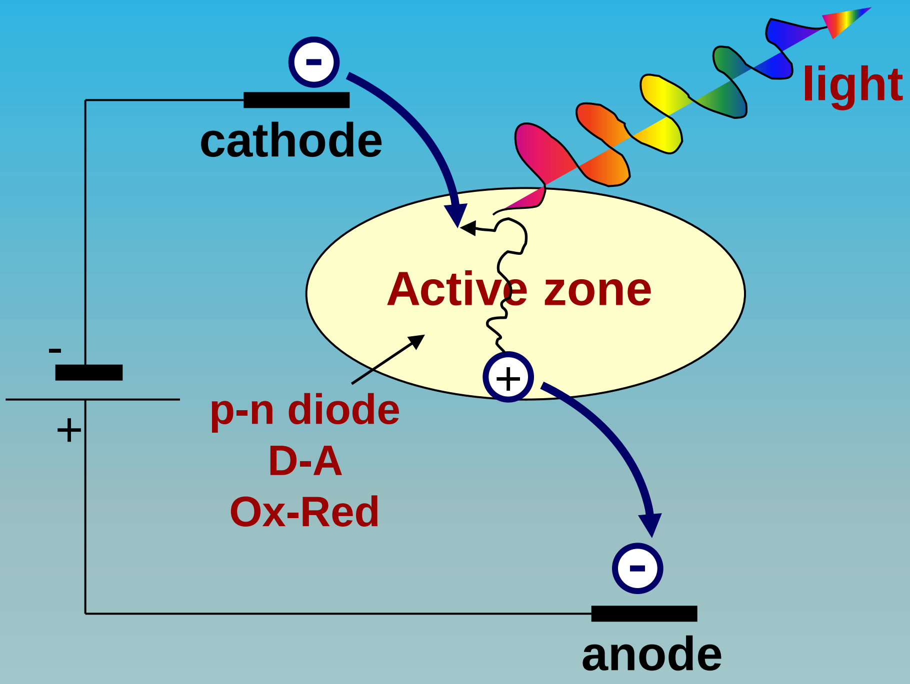
X. Yu et al. J. Lumin. 2006

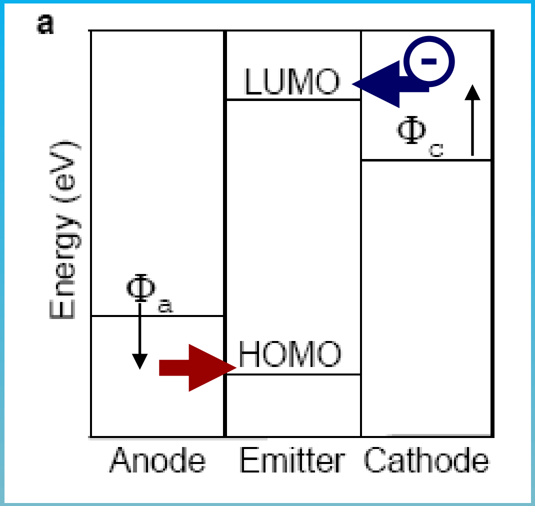
PMMA-ZnO „core-shell“

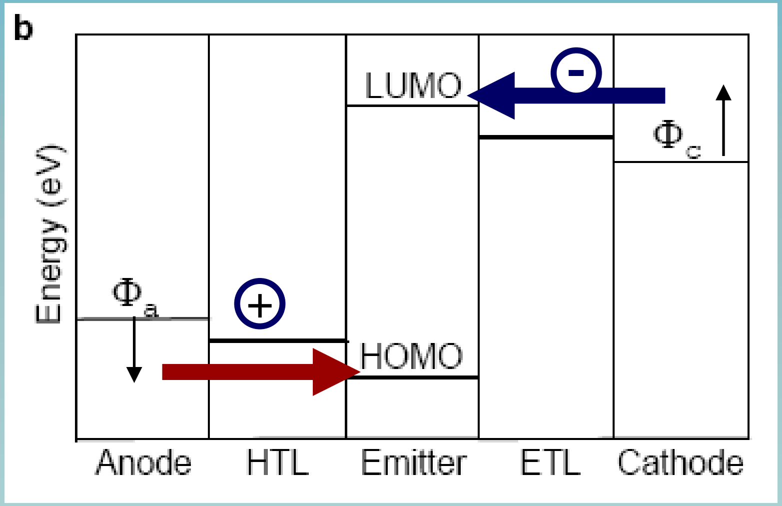


Electroluminescence

(inverse photovoltaic effect)







$$ELE = \eta = P_{light,out} / P_{el,in}$$

ELE = electroluminescence efficiency

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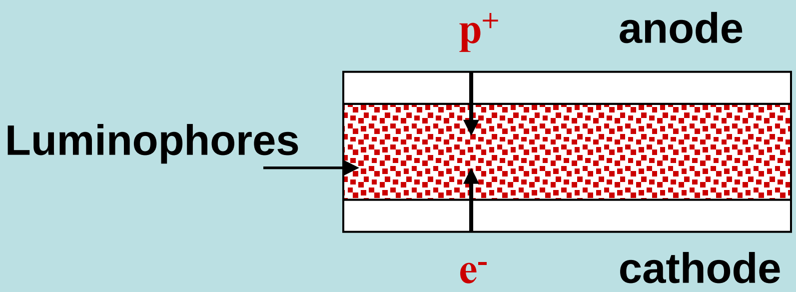
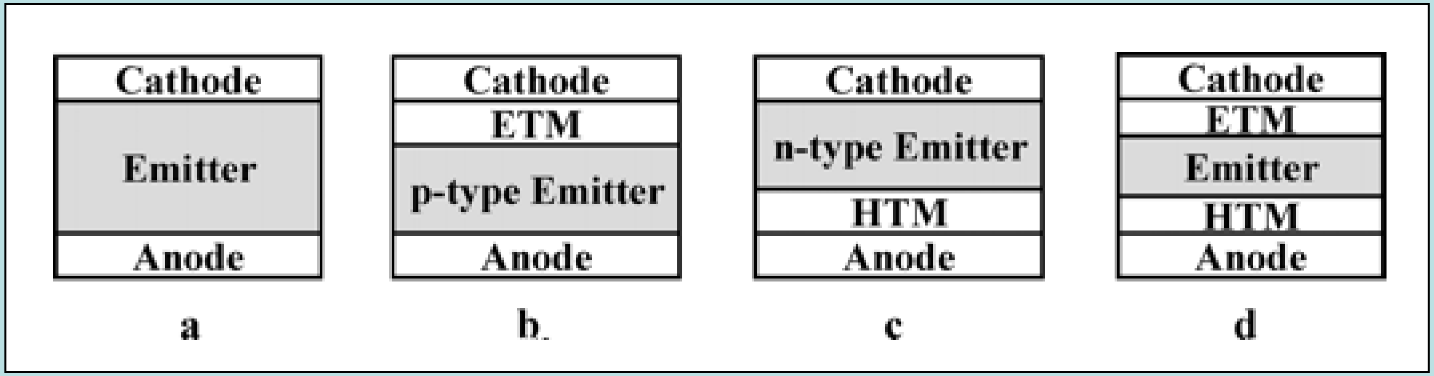
Cellule électrochimique d'écran électroluminescente

Principe de fonctionnement

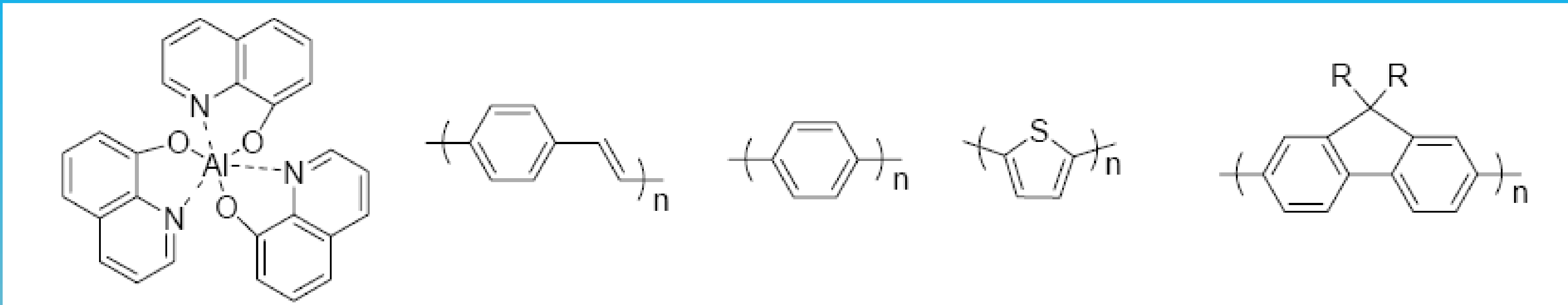
Couche entre 2 électrodes



Systèmes à plusieurs couches



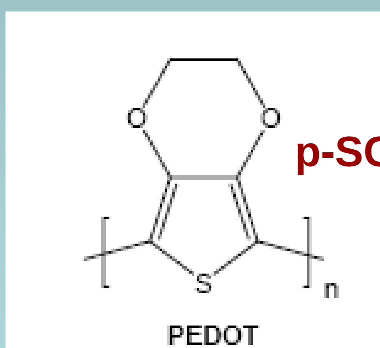
Molécules actives d’OLED



1 2 3 4 5

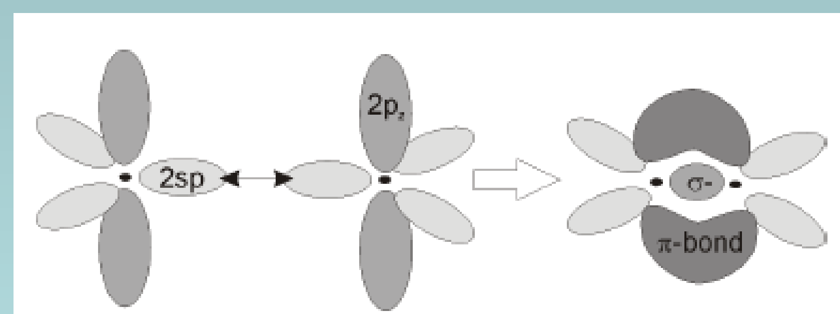
1. Alaq$_3$ = aluminium tris(8-hydroxyquinoline)
2. PPV = poly(p-phenylene-vinylene)
3. PPP = poly(1,4-phenylene)
4. PTh = polythiophenes
5. PF = polyfluorenes

PEDOT



p-SC

Poly-(3,4-ethylenedioxythiphene)



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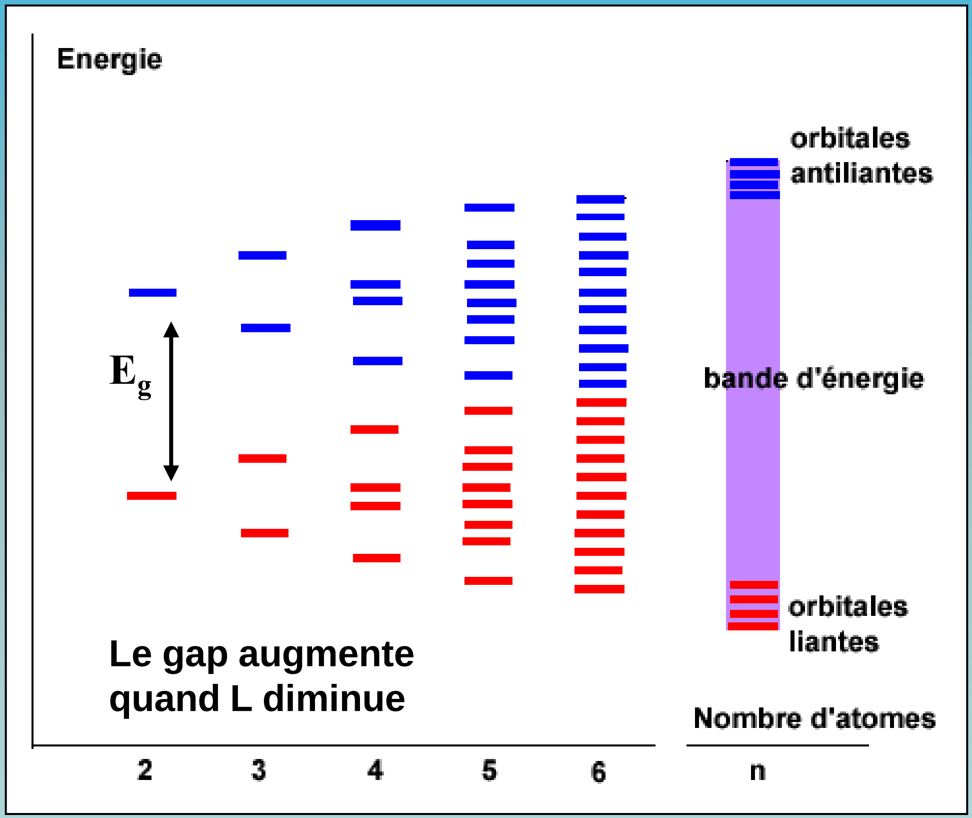
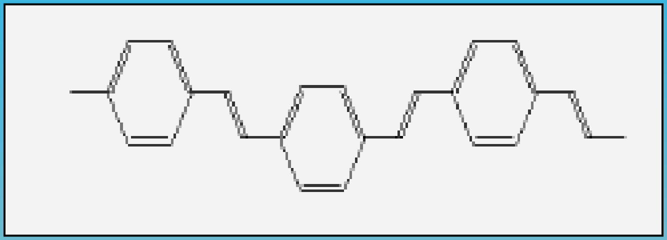
Les systèmes polymériques à doubles liaisons conjuguées

PPV = poly(phénylène-vinylène) E_g = 2,5 eV
émission jaune-vert





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Dopage des semi-conducteurs organiques

chimique ou électrochimique

Oxydation ⟶ **trous positifs** ⟶ **semi-conducteur ‘ p ’**

$$(CH)_x + xy(1,5I_2) \longrightarrow [CH^{y+}(I_3^-)_y]_x$$

Réduction ⟶ **électrons** ⟶ **semi-conducteur ‘n’**

$$(CH)_x + xyLi^+ + xye^- \longrightarrow [(Li^+)_y(CH)^{y-}]_x$$

La conductivité passe de 10^{-5} à 10^3 S/cm

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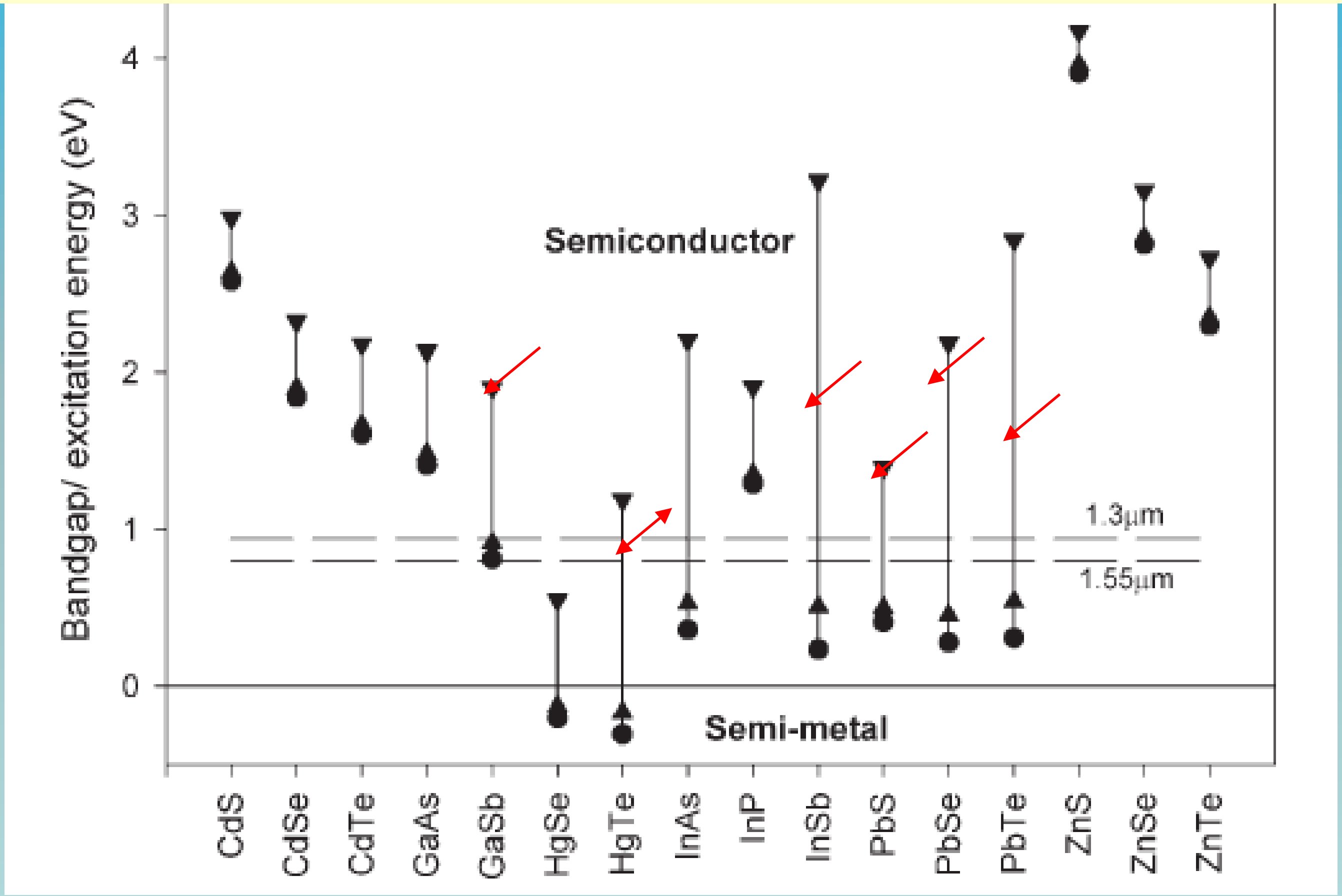
Électroluminescence avec nanostructures semi-conductrices

« Band gap engineering » avec nanocristaux quantiques
Taille moyenne: 3 nm – 10 nm



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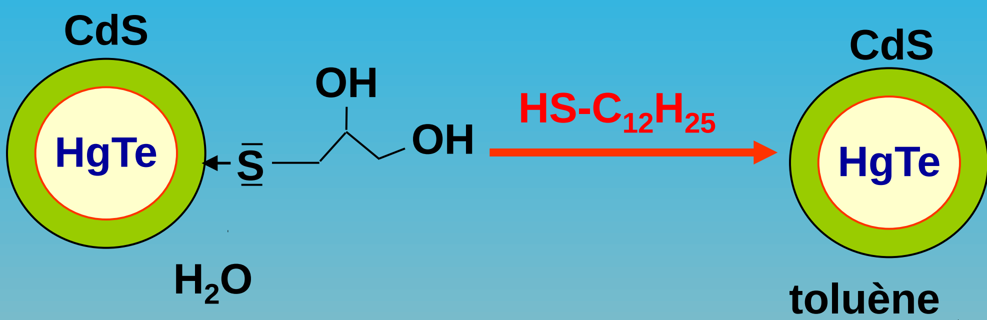
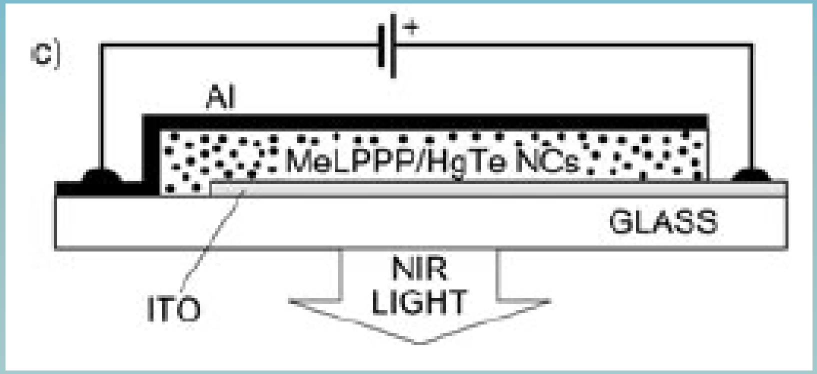
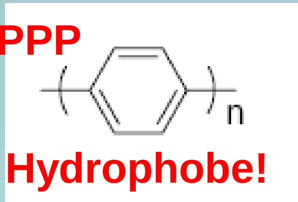


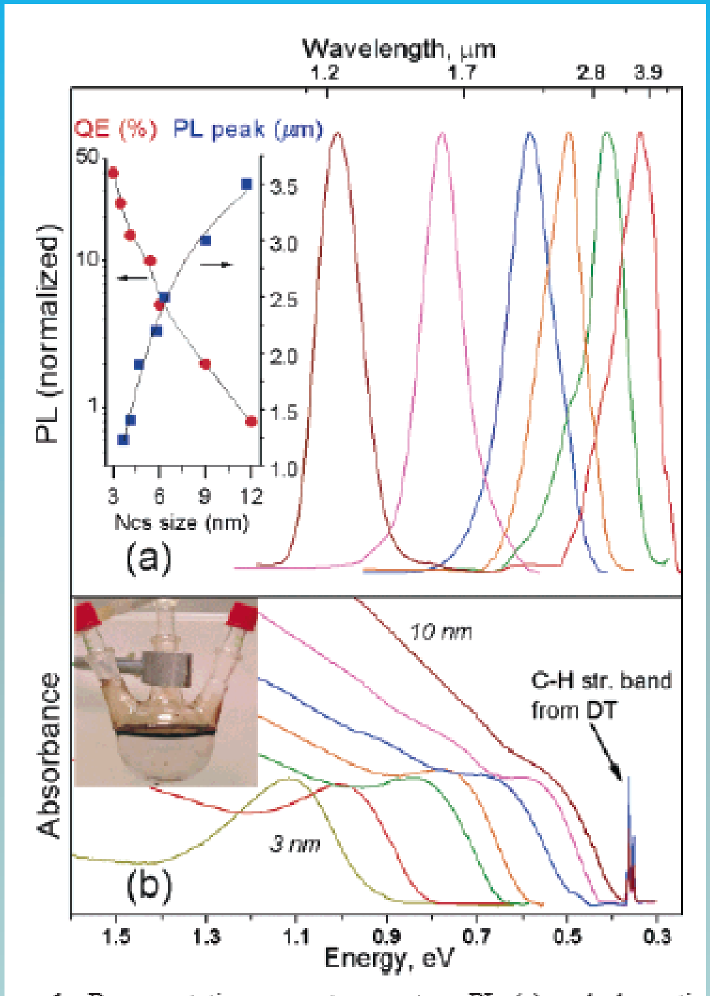
CdS
HgTe
S
OH
OH
H_2O
$HS\text{-}C_{12}H_{25}$
CdS
HgTe
toluène



c)
+
Al
MeLPPP/HgTe NCs
GLASS
ITO
NIR
LIGHT



PPP
n
Hydrophobe!



Wavelength, μm
1.2
1.7
2.8
3.9
QE (%)
PL peak (μm)
50
10
1
3.5
3.0
2.5
2.0
1.5
1.0
3
6
9
12
Ncs size (nm)
(a)
PL (normalized)
10 nm
C-H str. band
from DT
3 nm
(b)
Absorbance
1.5
1.3
1.1
0.9
0.7
0.5
0.3
Energy, eV

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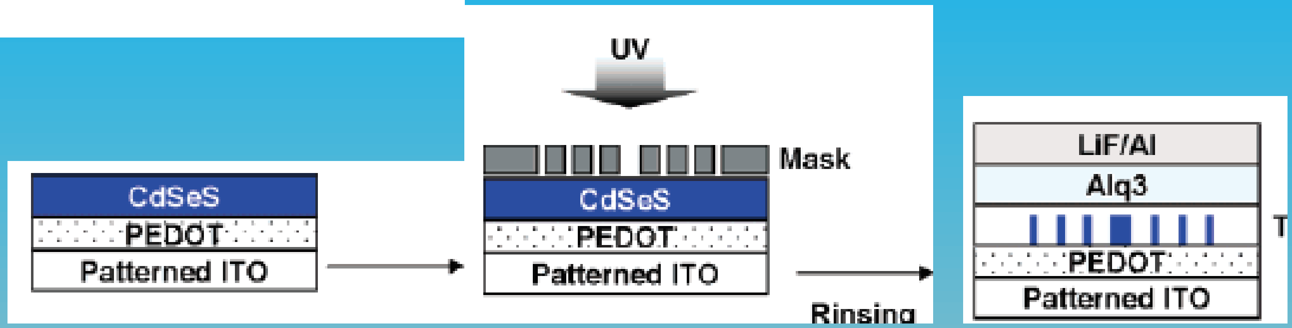
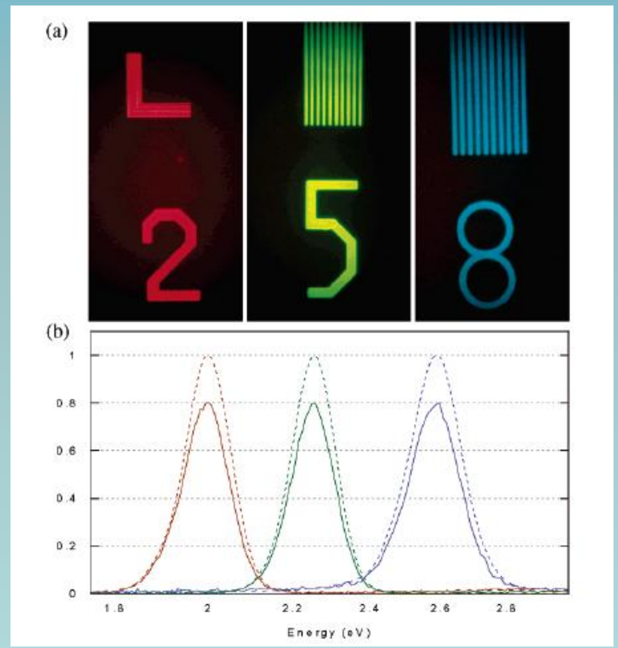
Langmuir **2006**, *22*, 2407−2410





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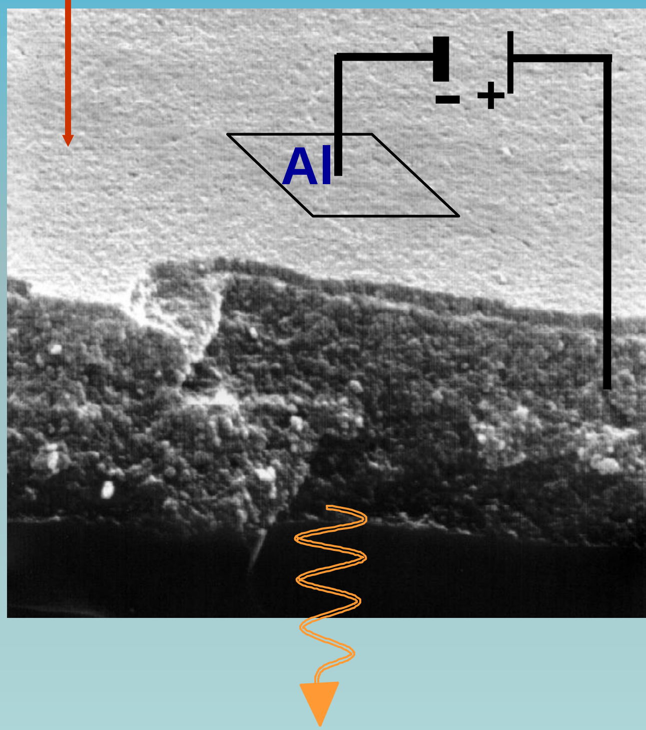
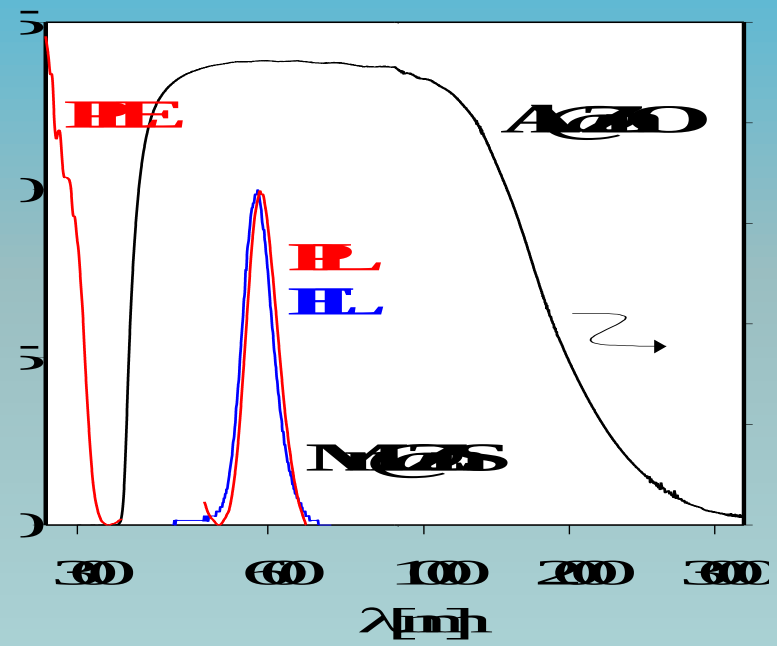
Electroluminescence in nanocrystalline bilayers
[Al^{3+}@ZnO / Mn^{2+}@ZnS - ZnI_2 / Al]

$ZnI_2(TBP)_2$ – infiltré





J. Phys. Chem. B 1998

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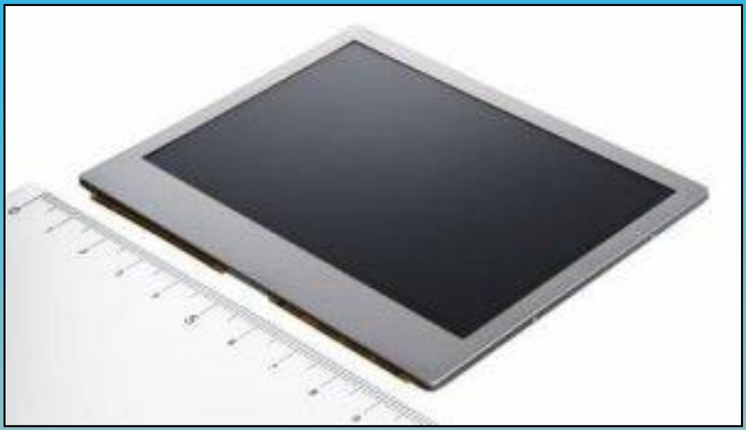
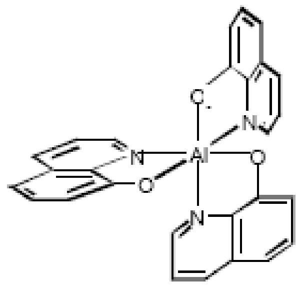
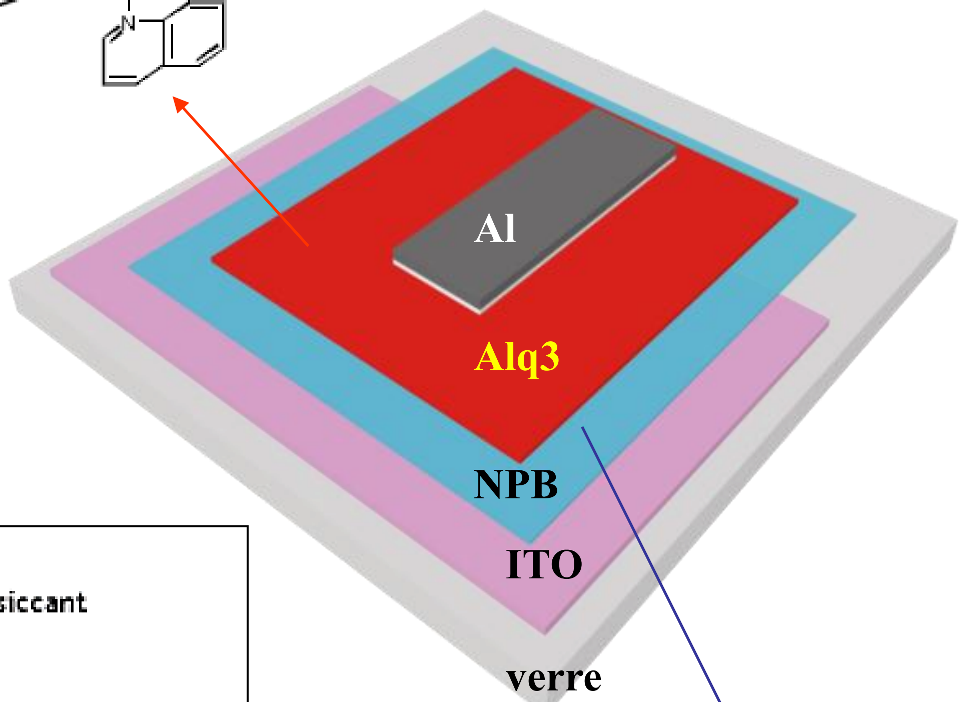
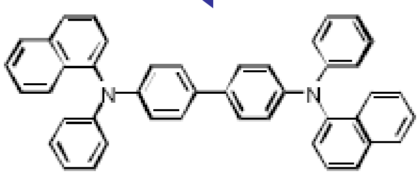
Flat panels

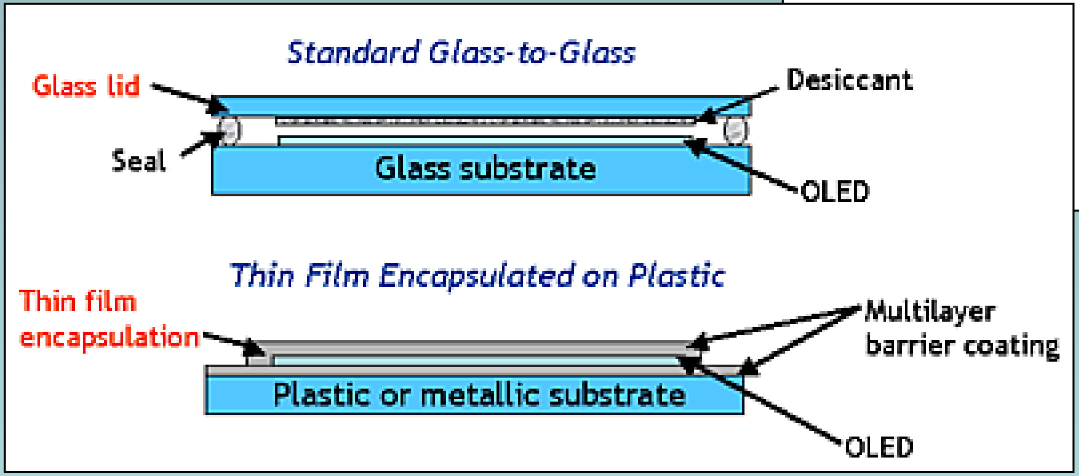








NBP



émission des deux côtés

Philips

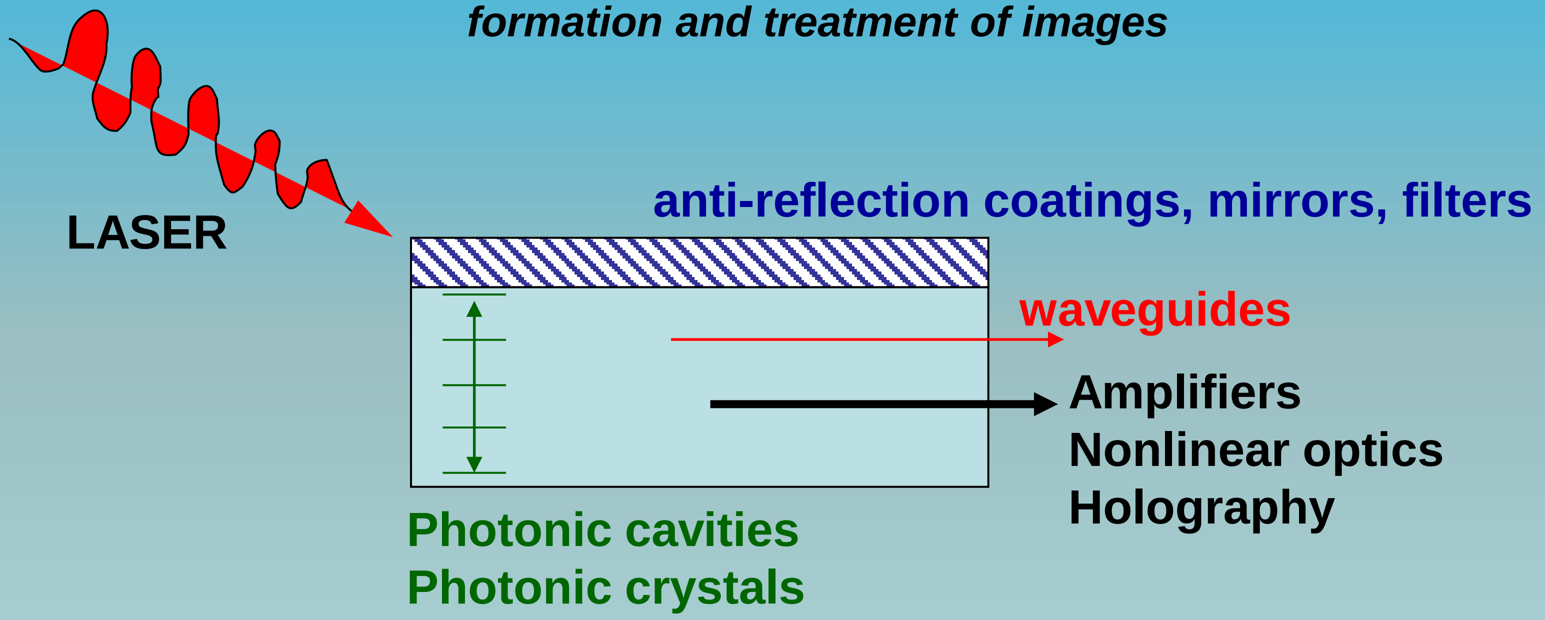
Rasoir Sensotec

Miniaturized plastic TV
(180000 pixel, at present 500000pixel)

3.4 Photonic nanomaterials

Photonics = Science of light

production, guiding and manipulation of light
formation and treatment of images



Waveguides (passive, active)

Coupling methods:

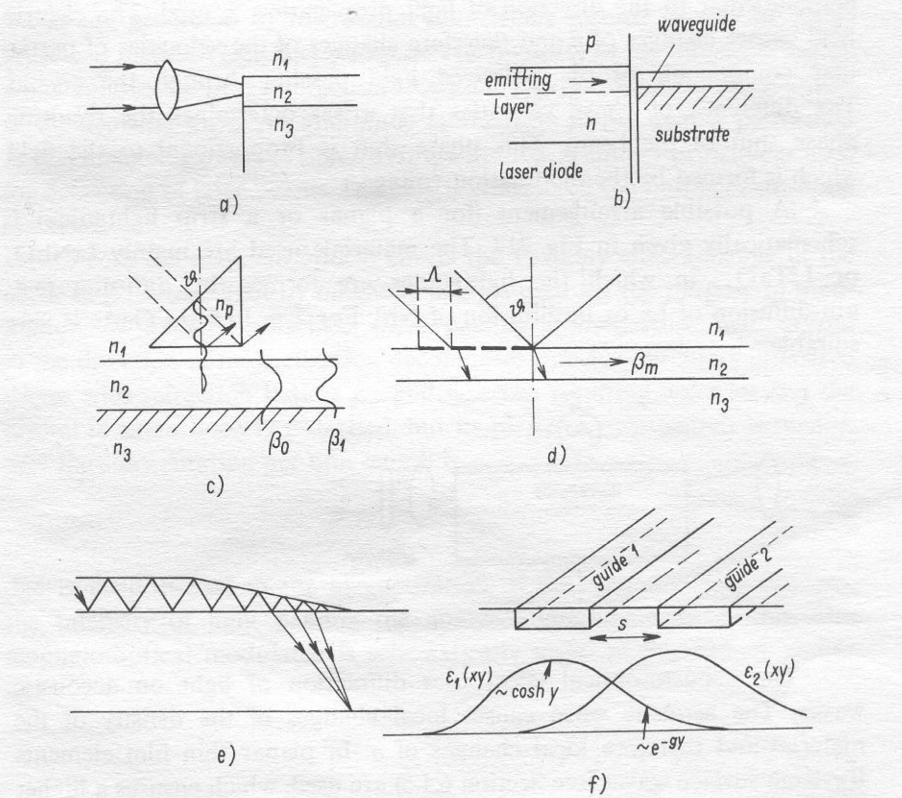


Fig. 213: Methods of optical coupling by means of: (a) a lens; (b) end-butt coupling; (c) prism; (d) grating; (e) tapered coupler; (f) coupling by optical tunneling.

Descartes rules:

1. Total reflection

$$n_{film} > n_{substrat}, n_{air}$$

2. Number of guided modes - m

$$m \propto \frac{e}{\lambda} \cdot n_{film}$$

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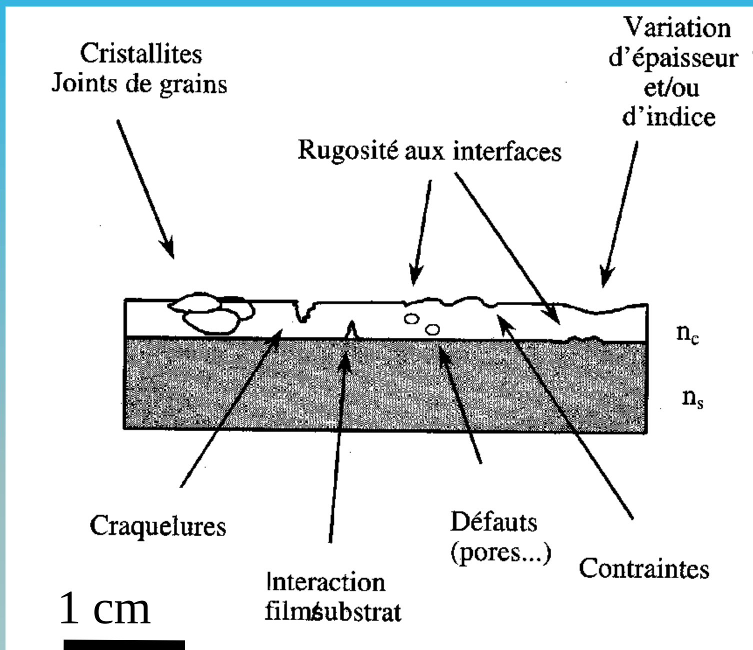
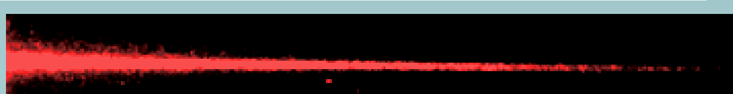
Propagation losses





Damping coefficient :
k_A [dB cm^{-1}]

$$k_A\left[dB\cdot cm^{-1}\right]=\frac{10}{x}OD=\frac{10}{x}\log\frac{I_0}{I}$$

Optical Absorption :

$$\alpha\left[cm^{-1}\right]=\frac{\ln 10}{10}\cdot k_A\left[dB\cdot cm^{-1}\right]$$

Light scattering in composites:

$$D.O.=0{,}325\cdot\Phi_p\cdot x\cdot R_p^3\cdot\frac{1}{\lambda^4}\left(\frac{n_{particule}}{n_{matrix}}-1\right)$$

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Desired quality:

1 dB km^{-1} (longe distances)
0,1 dB cm^{-1} (short distances)

sol-gel derived materials:

1. organosiloxanes:
k_A ~ 0,1 dB cm^{-1}

2. Metal oxides
TiO_2 (2,7) ; ZrO_2 (2,2) ; ZnO (2)
k_A ~ 0,5 - 2 dB cm^{-1}

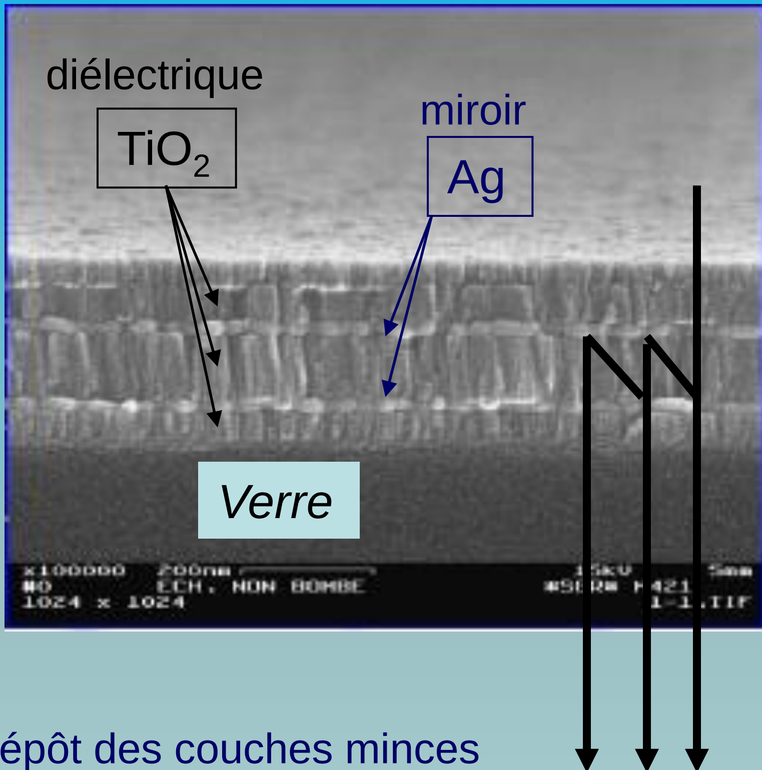
3. Polymers
PMMA
k_A ~ 10 dB cm^{-1}

Origin of opt. absorptions:

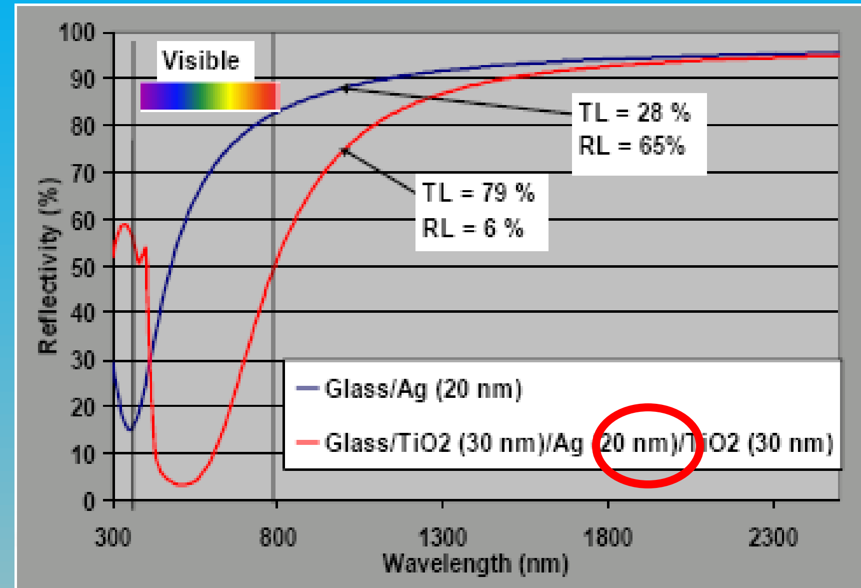
TELECOM domain 1 - 2 µm:
vibrations of OH’s, CH’s
Electronic transitions of foreign atoms

Silica: < 250 nm
Polysiloxanes: 300 - 400 nm
Polyphosphazenes: < 220 nm

Fabry-Pérot coatings



UV-vis



Dépôt des couches minces via “sputtering”

Source: St. Gobain
Herve Arribart

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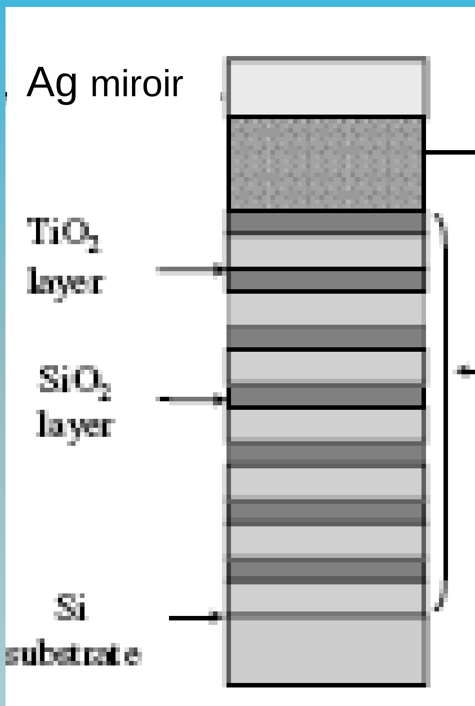
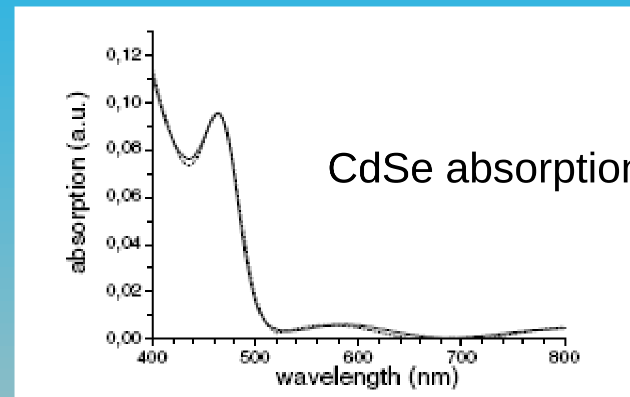
Sol-gel derived nanomaterials:

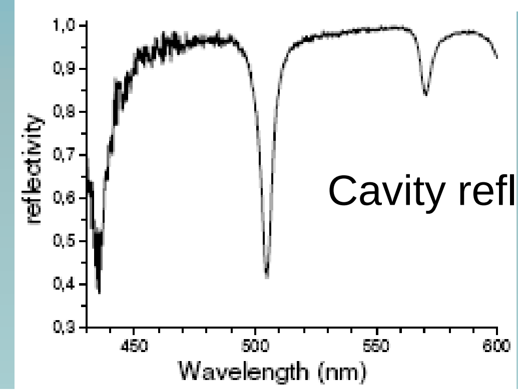
Bragg reflection produced in alternate SiO_2, TiO_2 multilayers
Microcavity composed of nanocrystalline ZrO_2 with 10% CdSe



Nanocomposite
ZrO_2/CdSe



CdSe absorption



Cavity reflection

Microcavity strongly doped with CdSe nanocrystals

S. Rabaste[1], J. Bellessa[1,a], C. Bonnand[1], J.C. Plenet[1], and L. Spanhel[2]

[1] Laboratoire de Physique de la Matière Condensée et des Nanostructures, Université Claude Bernard Lyon 1, CNRS-UMR 5586, 43 boulevard du 11 Novembre, 69622 Villeurbanne Cedex, France

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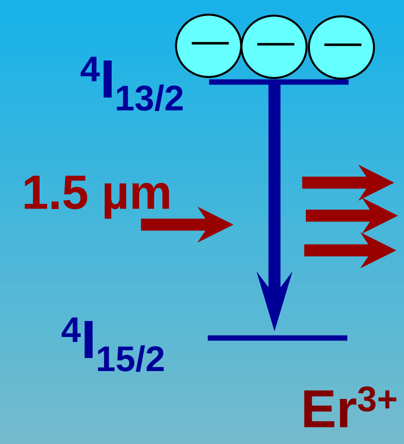
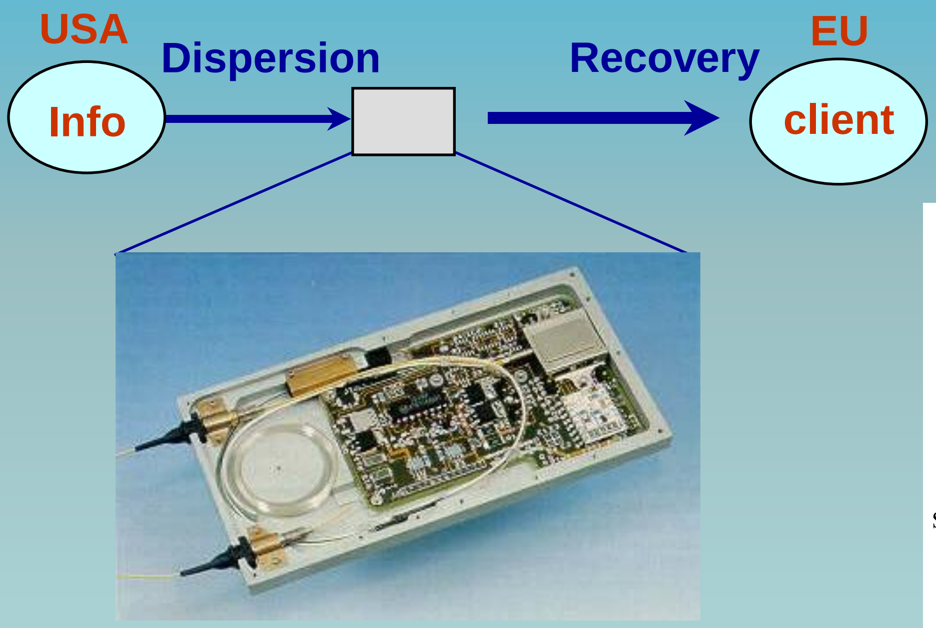
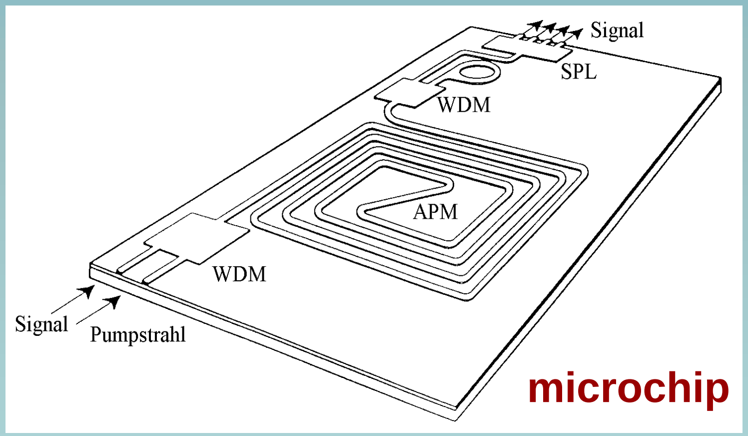
Light amplifiers in the NIR regime based on Er^{3+}- doped matrix





today



tomorrow

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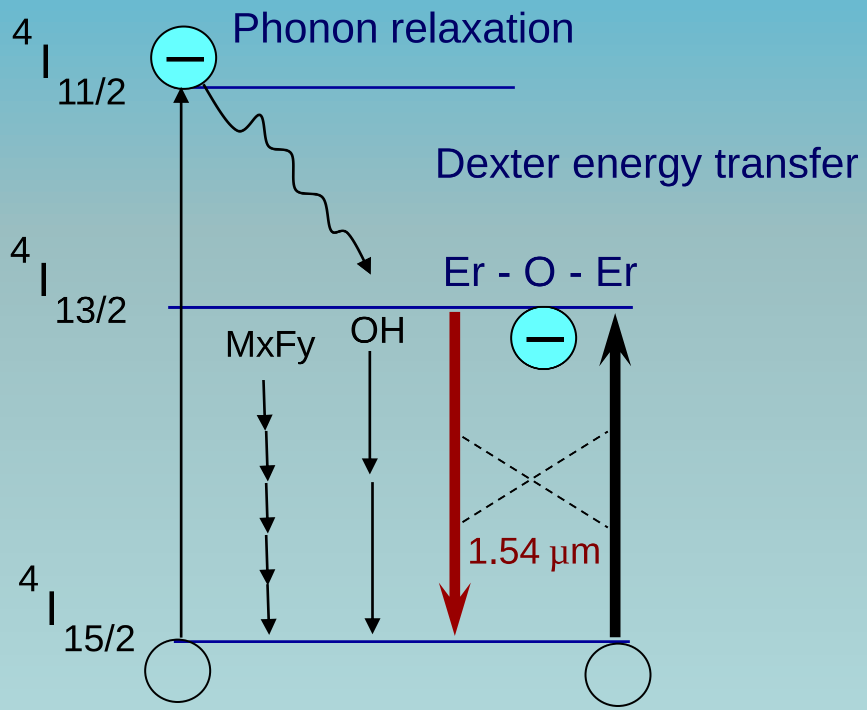
Critical parameters:

1. N = 10^{20} - 10^{21} Er^{3+}/cm^3
2. Mean life time of fluorescence (ms !)



Quantum yield of fluorescence

$$\eta = \frac{W_r}{W_r + W_{nr}} = \frac{W_r}{W_r + Ae^{-Bp}}$$

p = phonon = lattice vibration

p = Δ E/ ħ ω = 6537 cm^{-1}/ ħ ω

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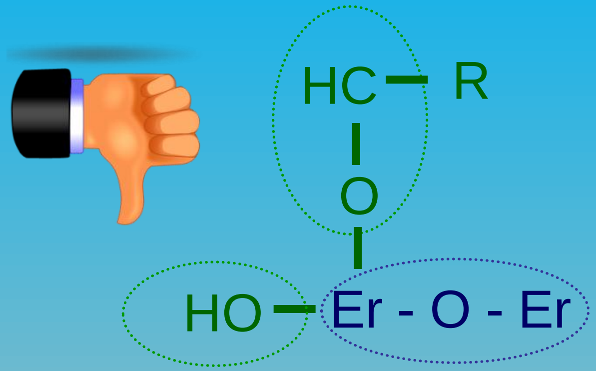
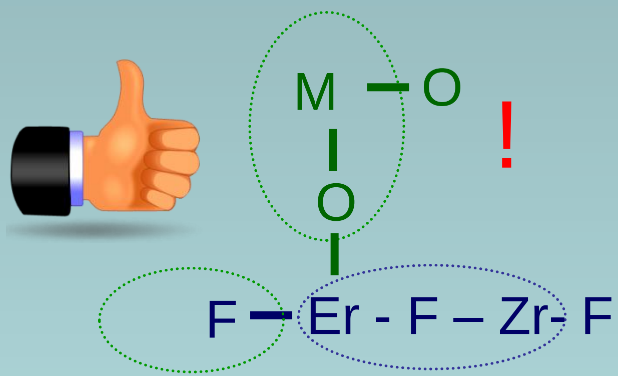
$$p = \Delta E / \hbar\,\omega = 6537\ cm^{-1} / \ \hbar\,\omega$$



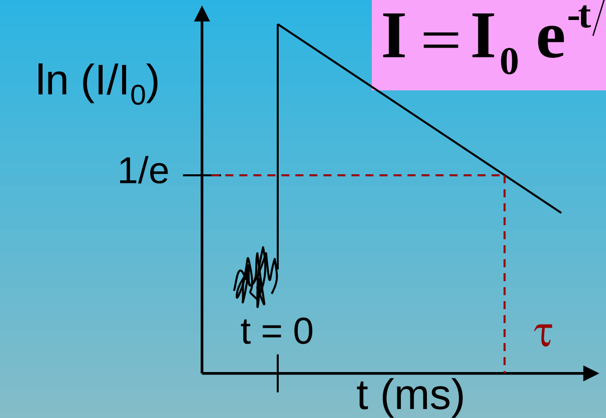
Vibration	$\hbar\omega$ (cm^{-1})	p - phonons
O-H	3000-3500	2
C-H	2800	2-3
P-O-P	1300	5
Si-O-Si	1000	6
M_xO_y M_xChalc_y	300-800	8-20
fluorures des métaux	200-400	15-30



Er $^{3+}$ non-agrégé

Absence des vibrations OH,CH

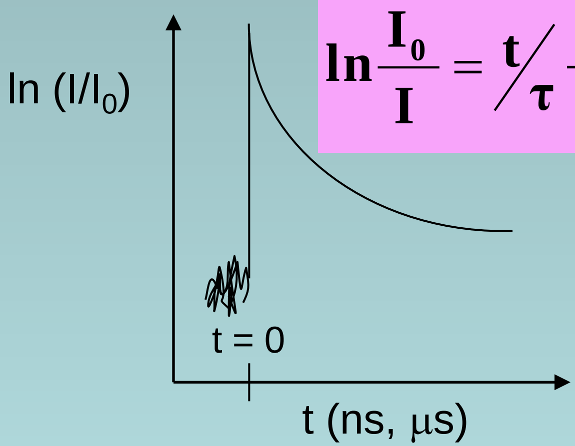
$$I = I_0\, e^{-t/\tau}$$



Er $^{3+}$ agrégé

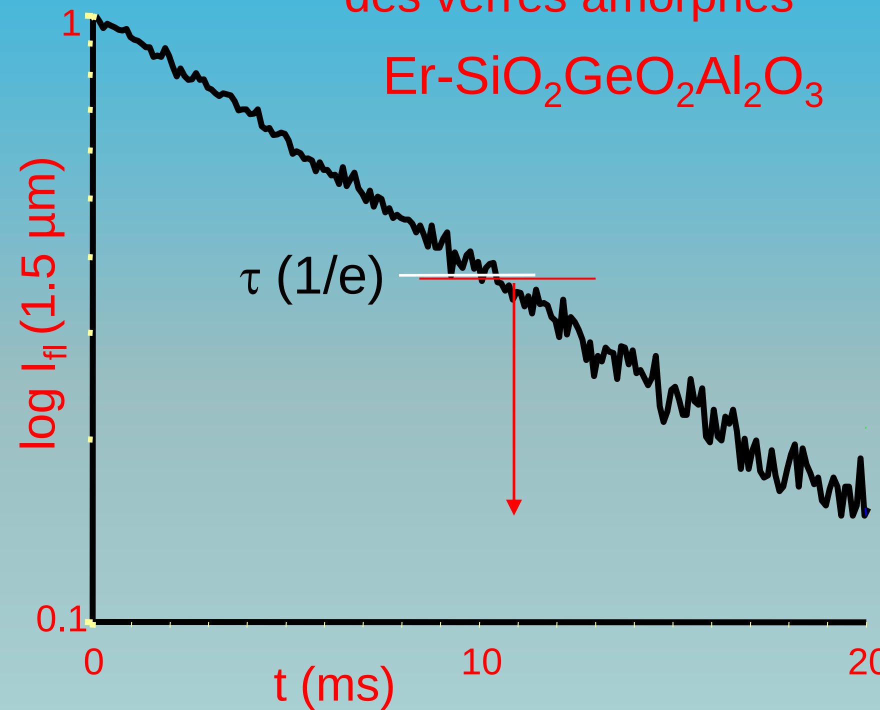
présence des vibrations OH,CH

$$\ln \frac{I_0}{I} = t/\tau + A\left(t/\tau\right)^{\beta}$$



Préformes industrielles des verres amorphes

$Er\text{-}SiO_2GeO_2Al_2O_3$



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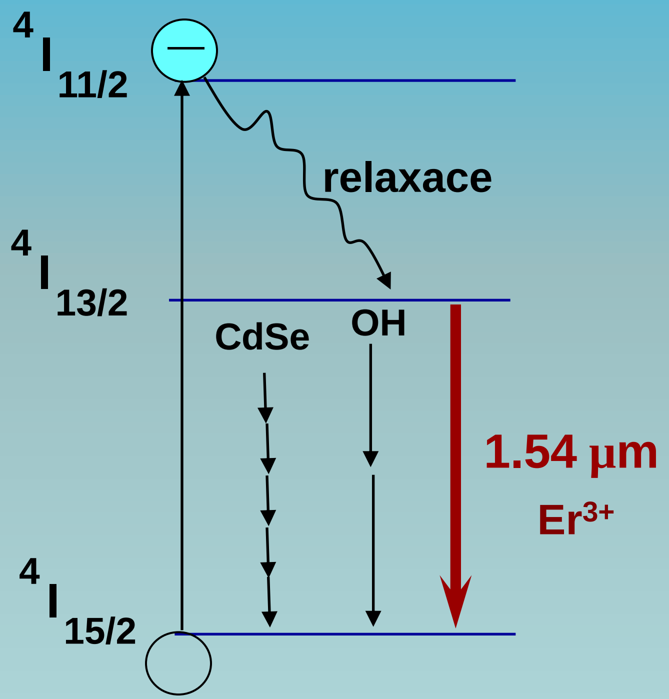
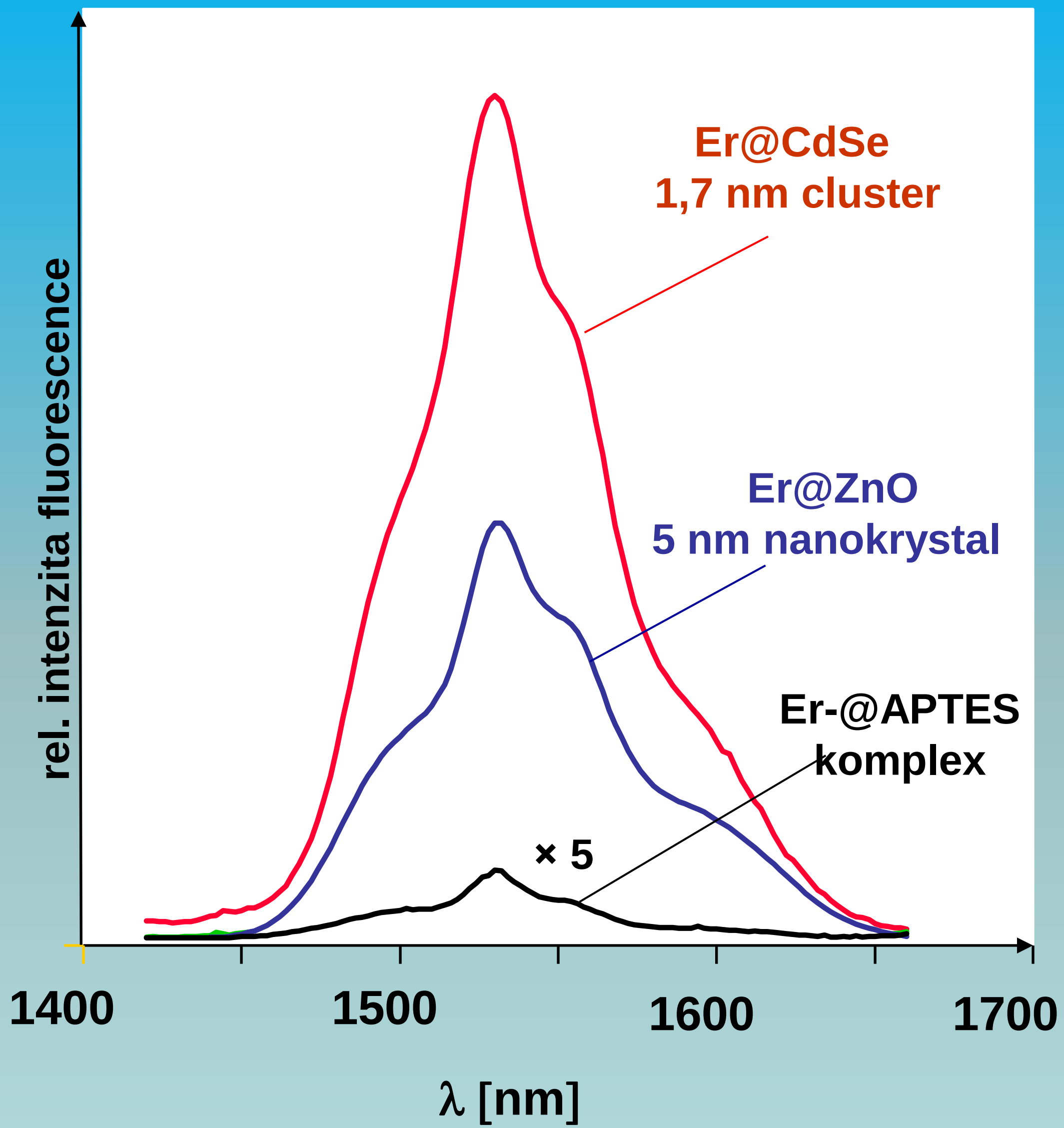
Multifononová relaxace ve fotoexcitovaných etanolických nanokoloidech





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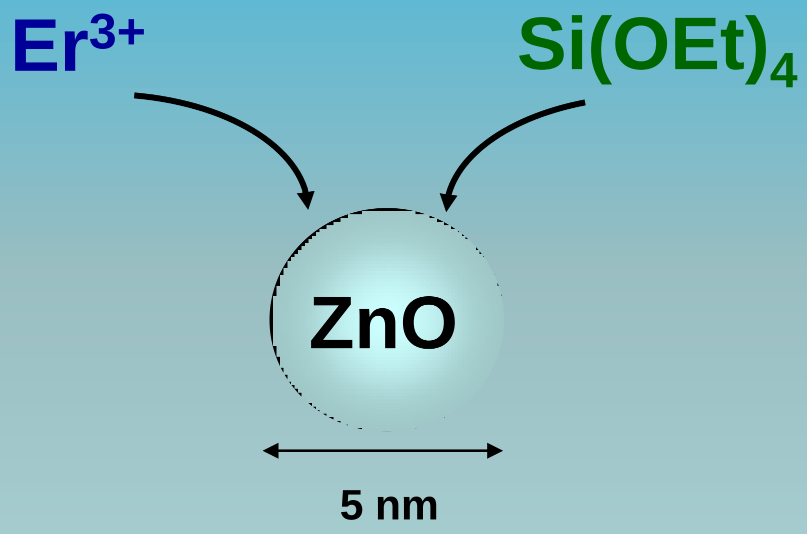
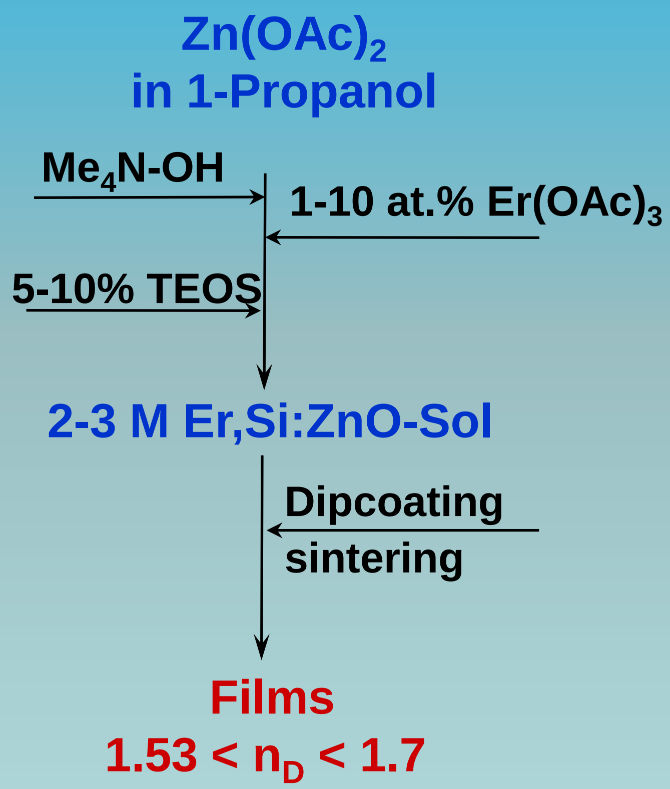
„co-dopování“ nanočástic ve 2M etanolickém solu ZnO

Er:ZnO synthesis





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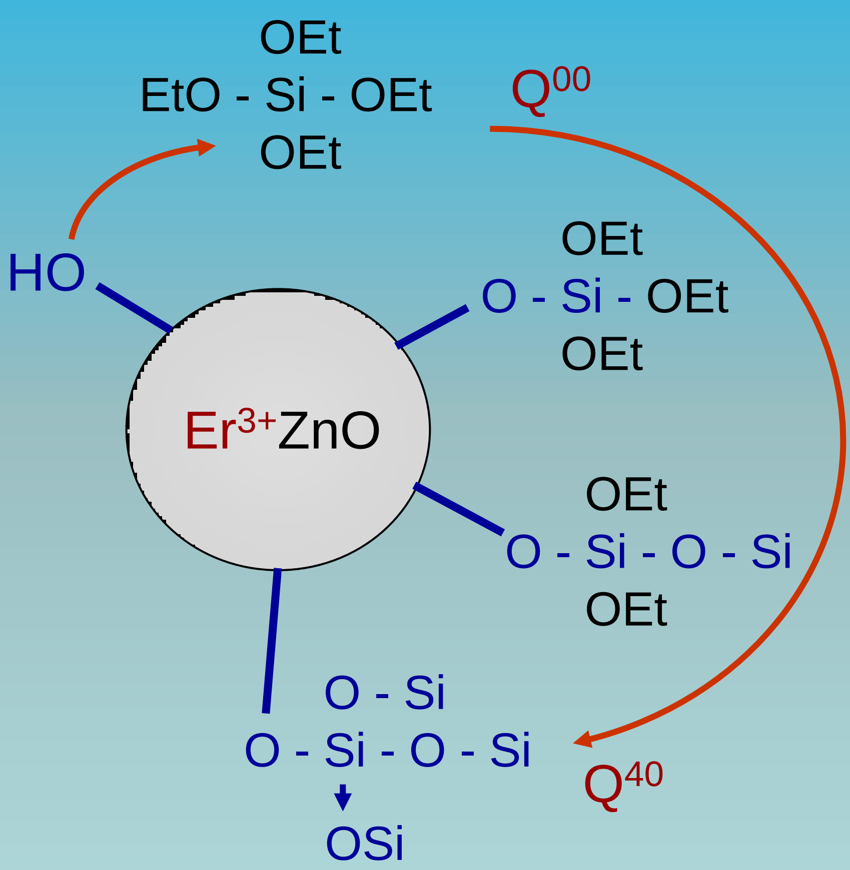
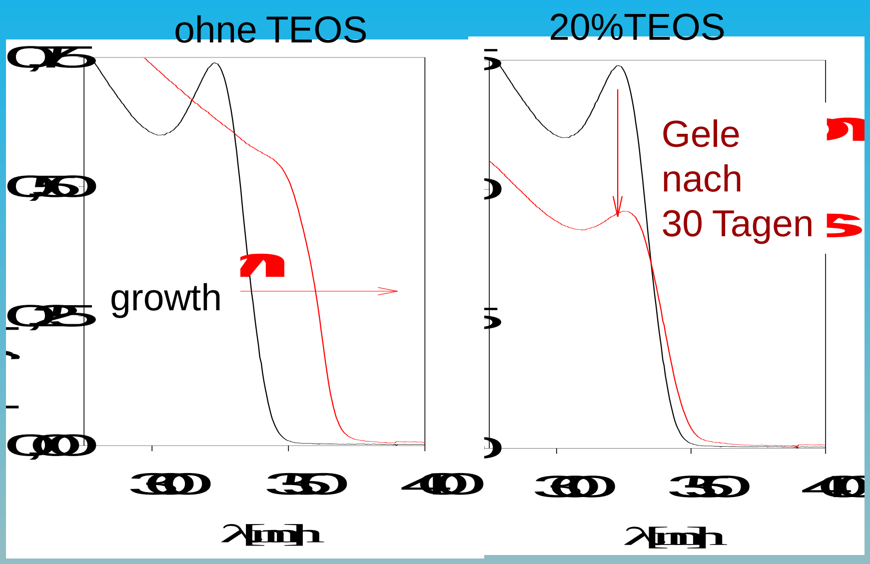
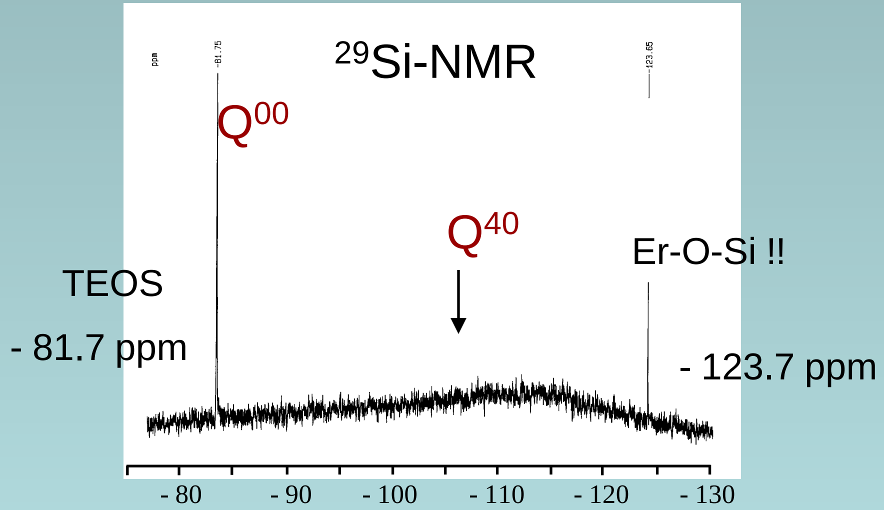
TEOS Kondensation in Er@ZnO Nanokolloiden



UV-vis





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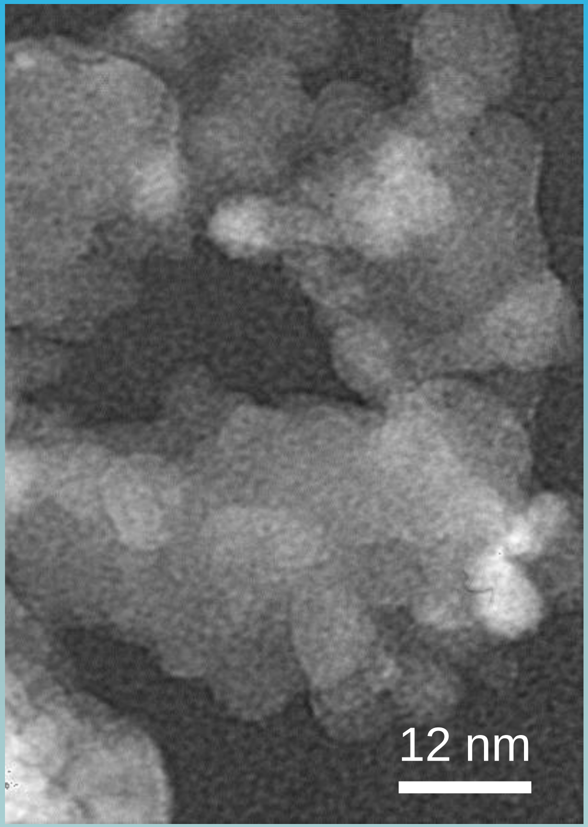
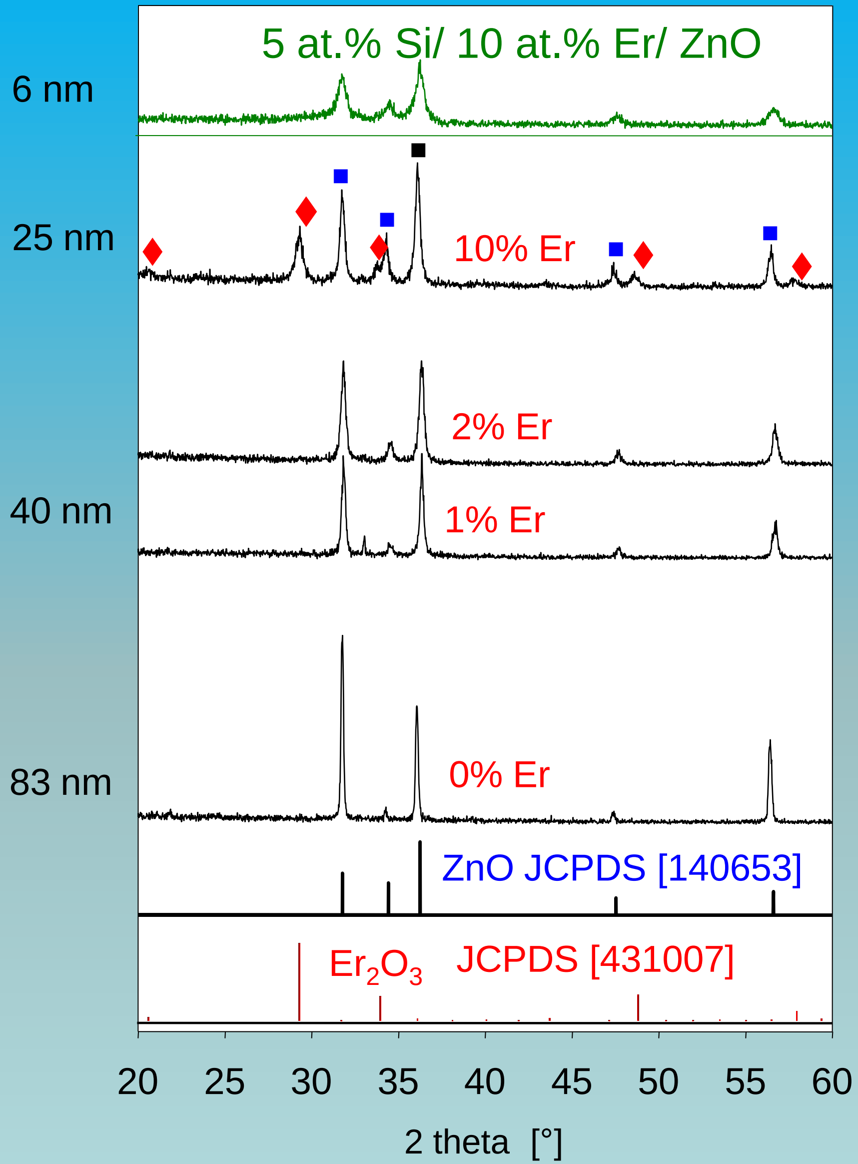
Filmsintern bei 750°C





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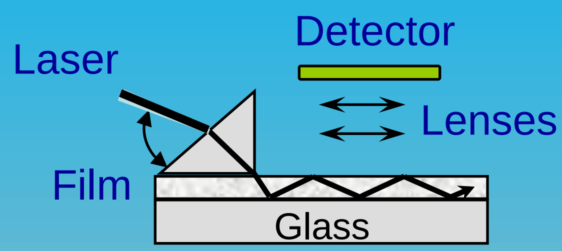
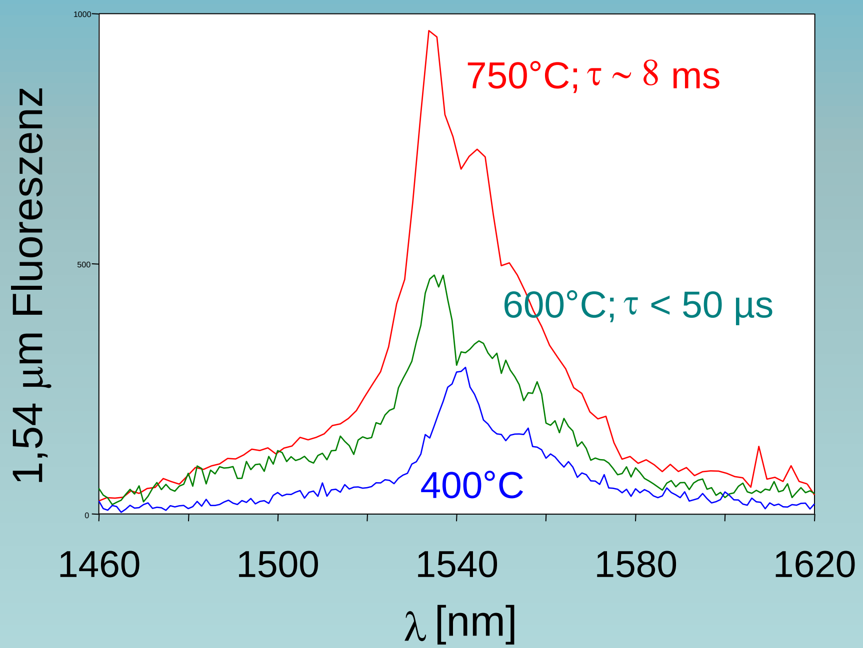
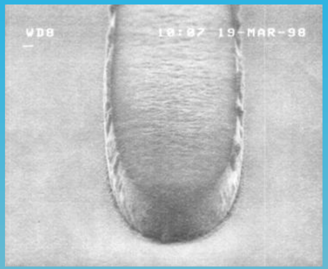
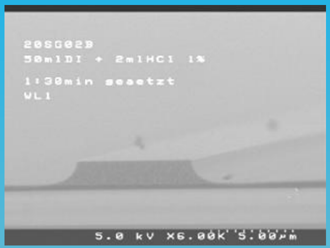
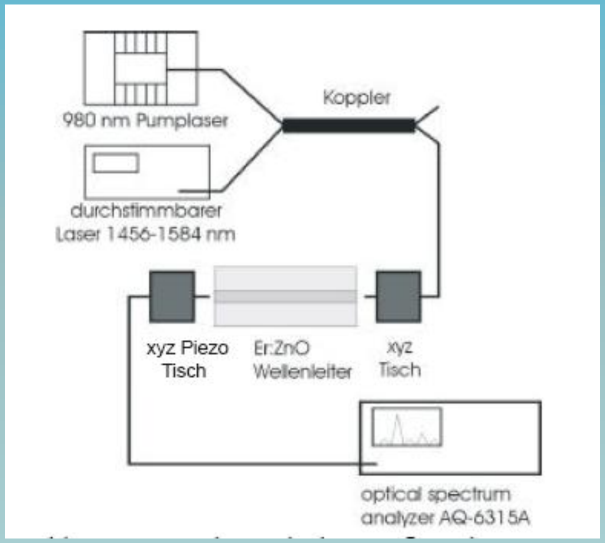
Er^{3+},Si^{4+}@ZnO wave guide







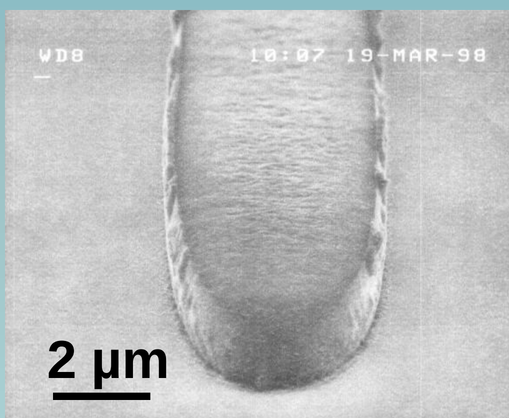




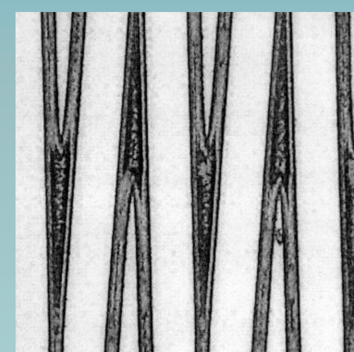
Optischer Netto Gewinn
1.5 µm : 3 dB/cm

Er^{3+},Si^{4+}@ZnO vlnovody a multiplexy

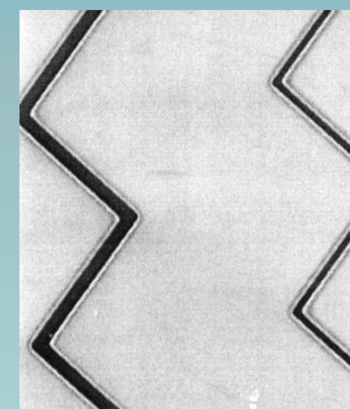
Fotolitografie



Laserová ablace



50 µm



100 µm

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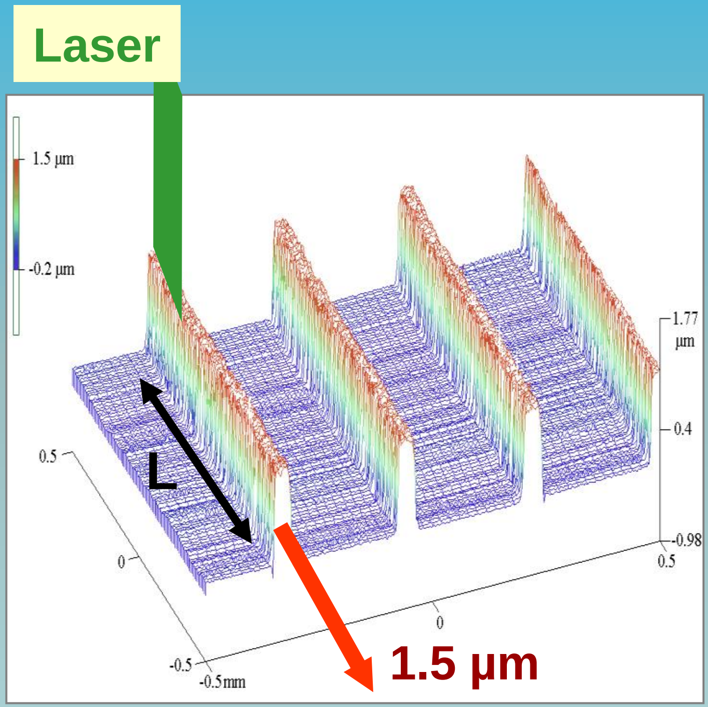
Optické zesílení ve vlnovodivých mikrostrukturách Er^{3+},Si^{4+}@ZnO



$$I(L) = \frac{I_{spon.}}{gL}\left[e^{gL}-1\right]$$

g = koeficient zesílení

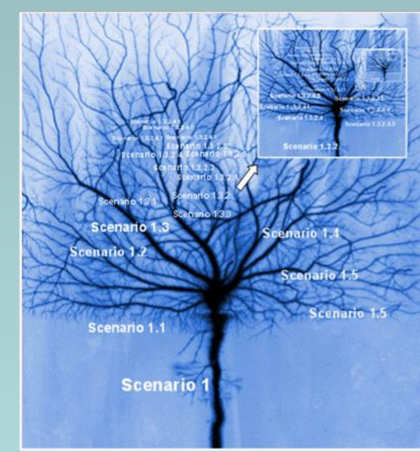
L = délka excitace

g = 80 - 100 cm^{-1}/500 µm

Výkon Laseru < 70 mW

Interní zesílení $I/I_0 \sim 50$

Chapter 4
Fractal approach to
physical chemistry and materials science



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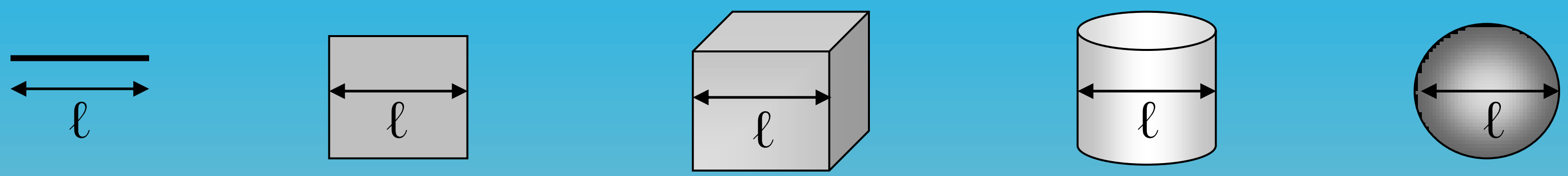
Chap. 4.1 Dimension d'un objet - D



$L_0 = \ell^1$ $A_0 = \ell^2$ $V_0 = \ell^3$ $= (\pi/4)\ell^3$ $= (\pi/6)\ell^3$

On se propose d'occuper l'espace de dimension 1, 2 ou 3 de la longueur latérale - L avec un nombre N des initiateurs (molécules) ayant longueur (de liaison chimique) ℓ

$$\left.\begin{array}{l} N(L) = m\,L^1 \\ N(L) = n\,L^2 \\ N(L) = p\,L^3 \end{array}\right\}$$

$$N(L) \sim C\,L^D$$

$$\log N(L) = \log C + D \log L$$

$$D = \frac{\log N}{\log L}$$

Relation générale pour les objets de n'importe quelle dimension

$0 < D < 3$!

L. Spanhel

Concept of dimension - D in regular systems

$$\mathbf{D} = \lim_{L \to \infty} \frac{\log N}{\log L}$$

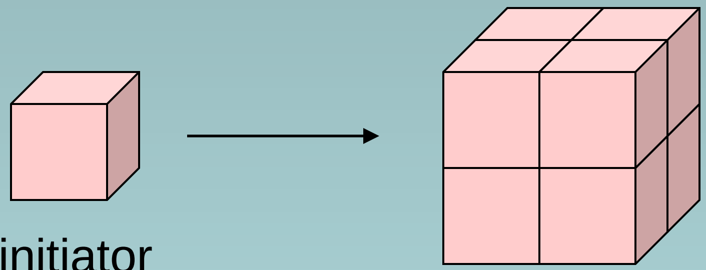
D = dimension of an object
N = generator (collection of initiators)
L = linear size of the object

Regular objects are characterised by an integer dimension (D = 1, 2 or 3); Their density does not change

$$\mathbf{D(line)} = \lim_{L \to \infty} \frac{\log 2}{\log 2} = 1$$

$$\mathbf{D(square)} = \lim_{L \to \infty} \frac{\log 4}{\log 2} = 2$$

$$\mathbf{D(cube)} = \lim_{L \to \infty} \frac{\log 8}{\log 2} = 3$$



initiator

generator
N = 2 (line)
N = 4 (square)
N = 8 (cube)

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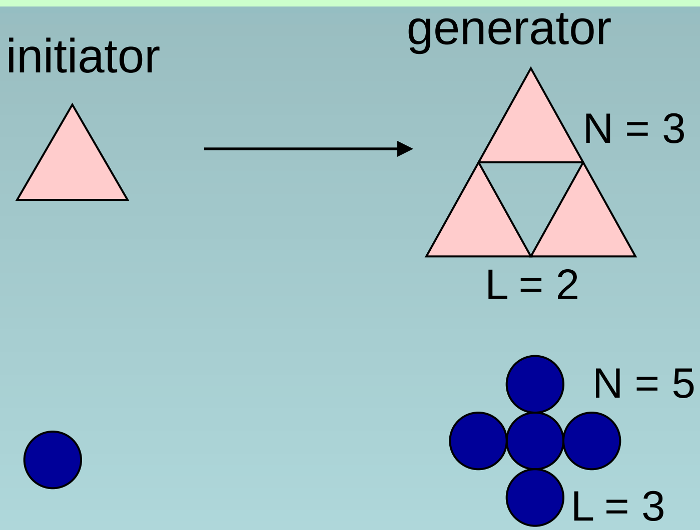
La dimension fractale

(Introduit par Benoît Mandelbrot)

$$\mathbf{D} = \lim_{L \to \infty} \frac{\log N}{\log L}$$

D = dimension of an object
N = generator (collection of initiators)
L = linear size of the object

Fractal objects are characterised by a non-integer dimension (1 < D < 3); Their density drops with increasing size



$$\mathbf{D\,(triangle)} = \lim_{L \to \infty} \frac{\log 3}{\log 2} = 1{,}584$$

$$\mathbf{D\,(carré)} = \lim_{L \to \infty} \frac{\log 5}{\log 3} = 1{,}465$$

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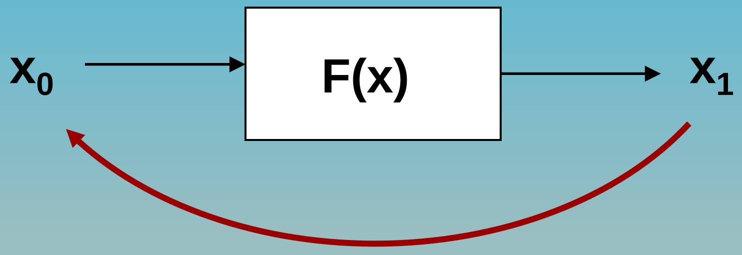
Fractal objects are self-similar

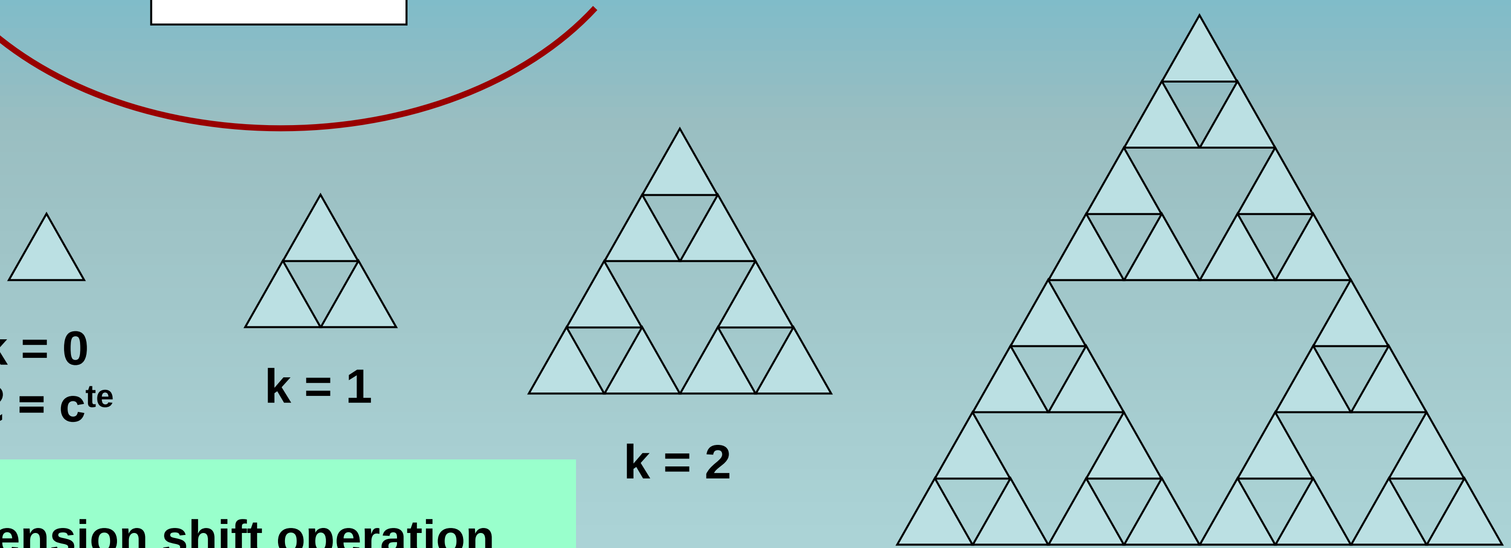
Constructions répétitives
("iteration based construction")

$$D = \lim_{L \to \infty} \frac{\log N^k}{\log L^k} = \frac{\log 3^k}{\log 2^k}$$

Analogie mathématique



$N = 3^k, L = 2^k$



k = 0
$\ell = c^{te}$

k = 1

k = 2

k = 3

extension shift operation

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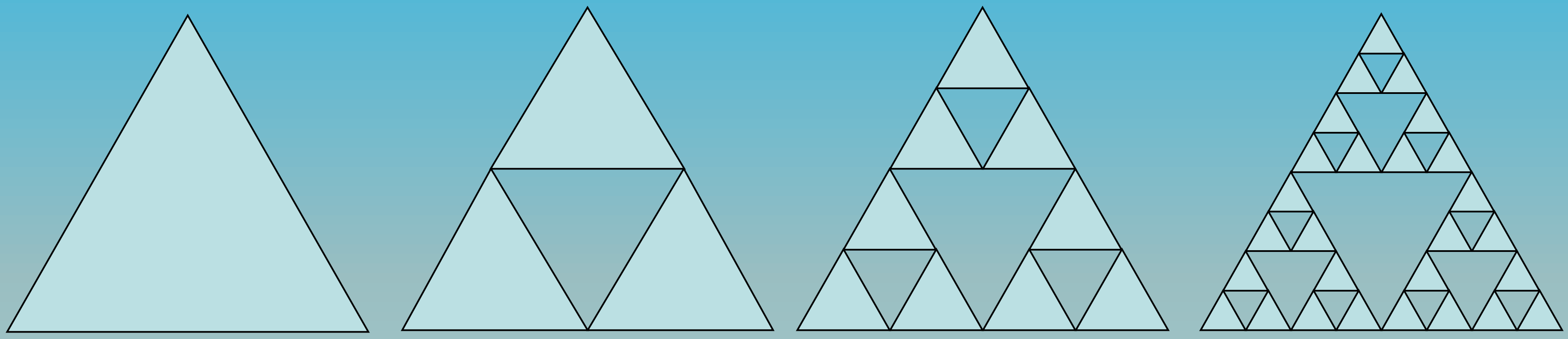
$$D = \lim_{\ell \to 0} \frac{\log N^{k}}{\log (1/\ell)^{k}} = \frac{\log 3^{k}}{\log (1/2)^{k}}$$



k = 0

$L = c^{te}$

k = 1

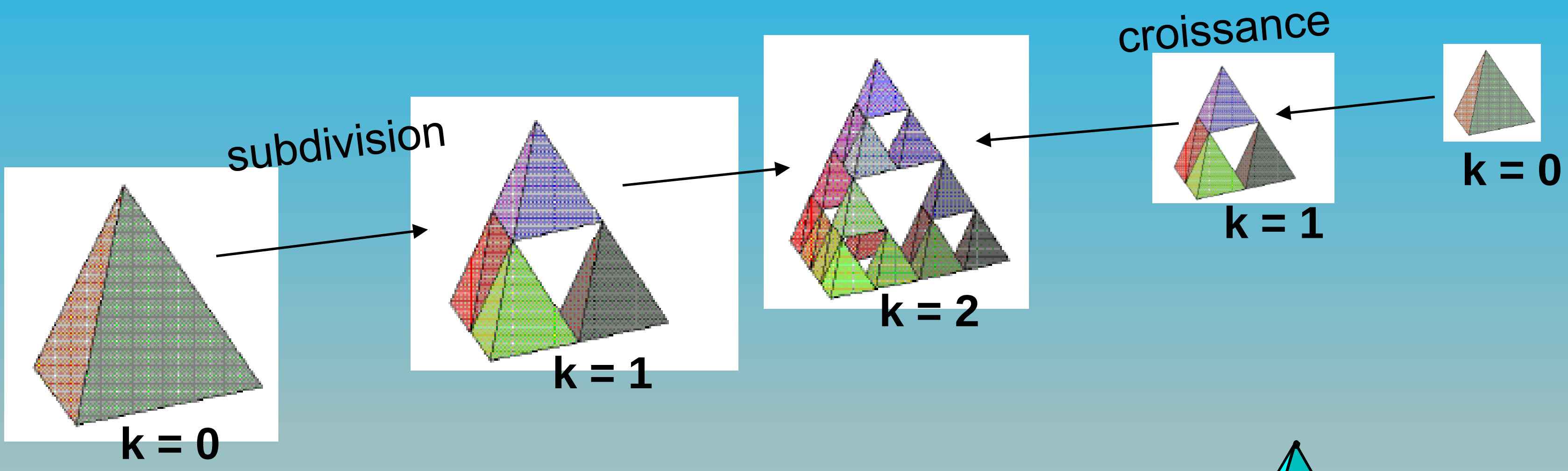
k = 2

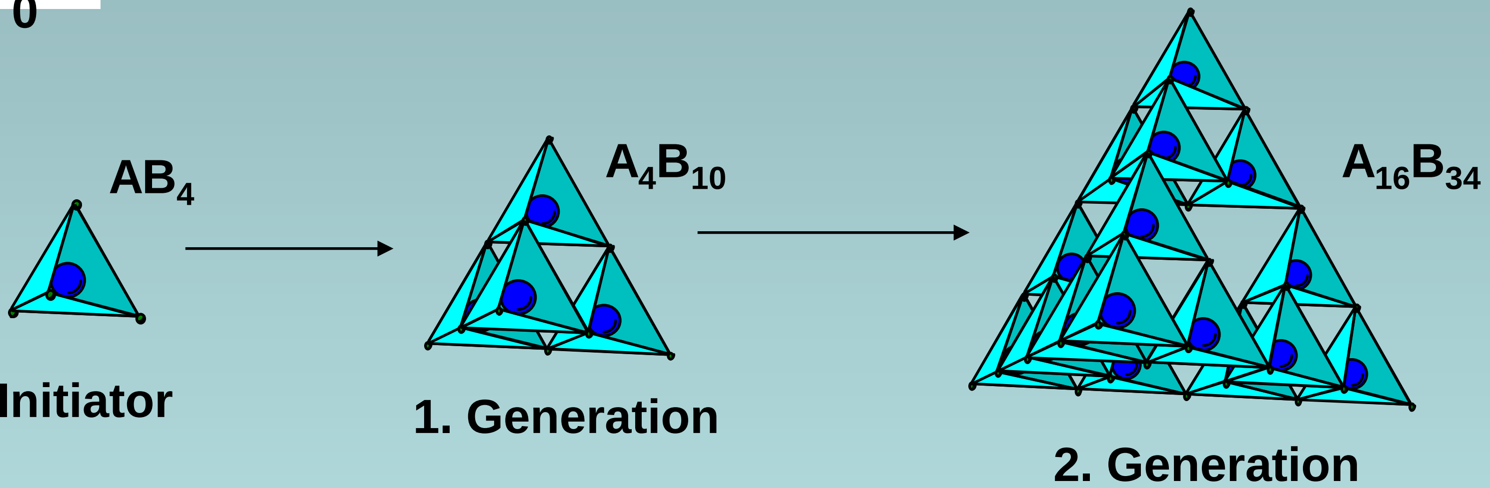
k = 3

contraction shift operation

Fractal Tetrahedron

$$D = \frac{\log\ 4}{\log\ 2} = 2 \qquad N = 4^{k},\ L = 2^{k}$$





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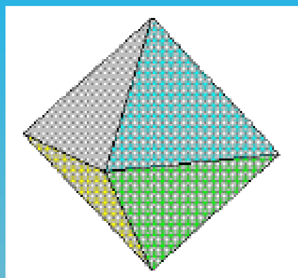
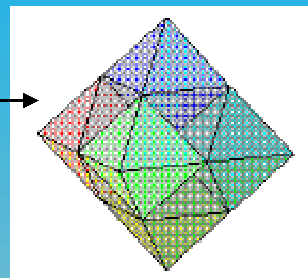
Fractal Octahedron



k = 0

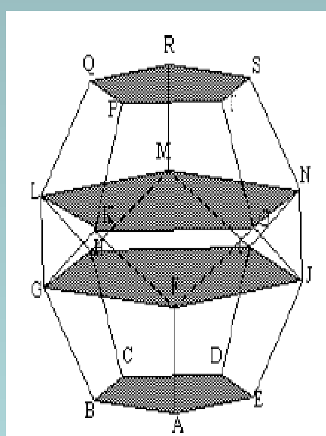


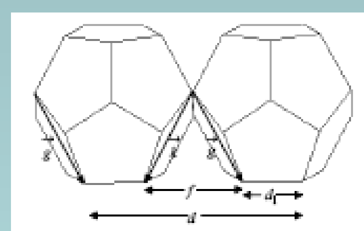
k = 1

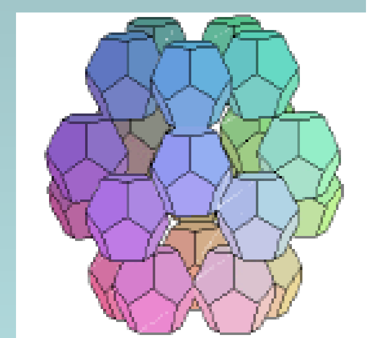
$$\mathbf{D} = \frac{\log\ 6}{\log\ 2} = 2{,}585 \quad \mathbf{N = 6^{k}, L = 2^{k}}$$

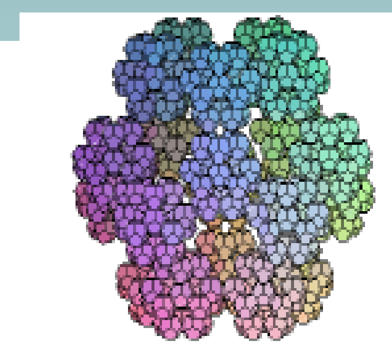
Fractal Dodecahedron

$$\mathbf{D} = \frac{\log\ 20}{\log\ \mathbf{d}/\mathbf{d}_1} = 2{,}329$$









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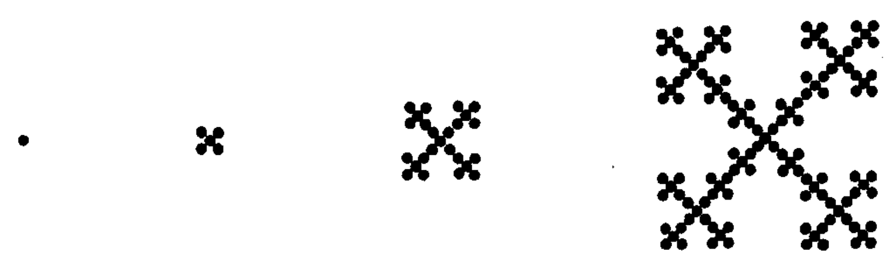
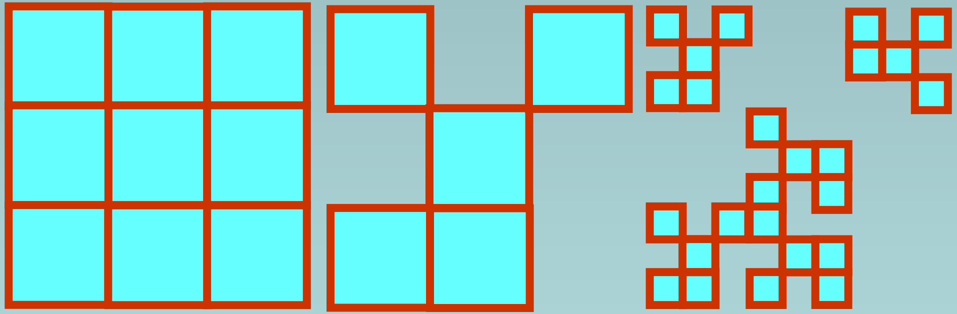
Il y a deux structures différentes
et pourtant ayant la même dimension fractale

Structures fractales selon Vicsek: D_f = log 5 / log 3 ~ 1.465



Croissance déterministe



Gravure à l 'acide (ou corrosion) stochastique

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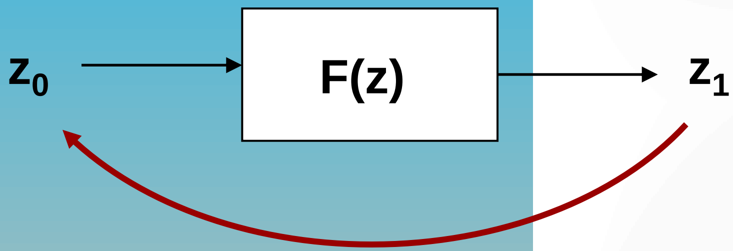
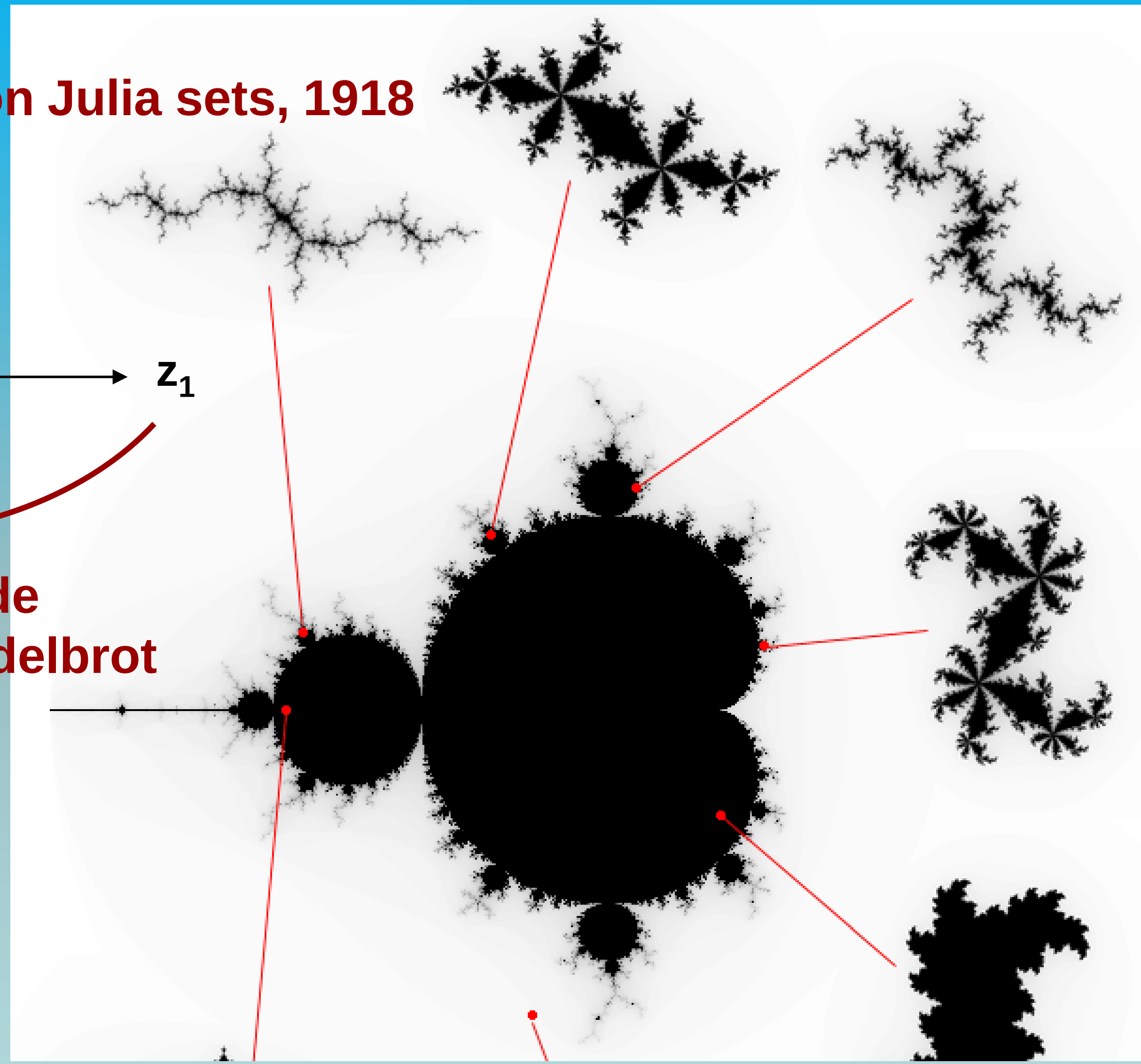
Gaston Julia sets, 1918

$$F(z) = z^2 - \mu$$

$$z = i\,c_1 + c_2$$



La pomme de Benoît Mandelbrot



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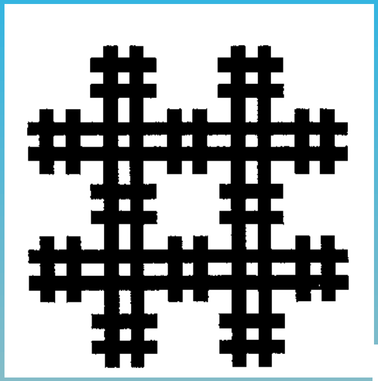
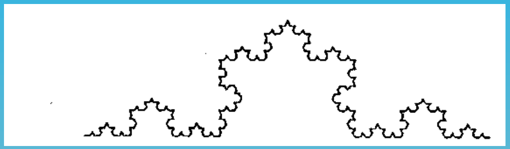
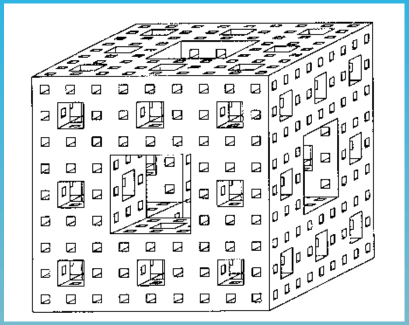
Sierpinski carpet

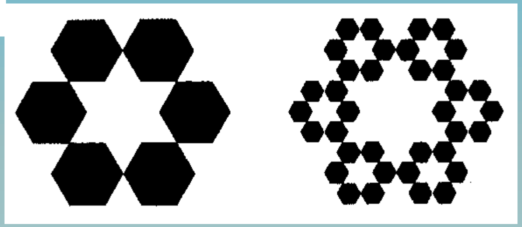


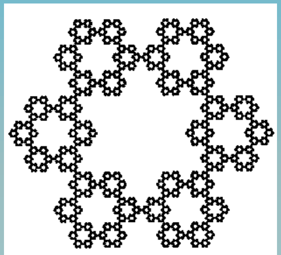
Koch curve



Menger sponge

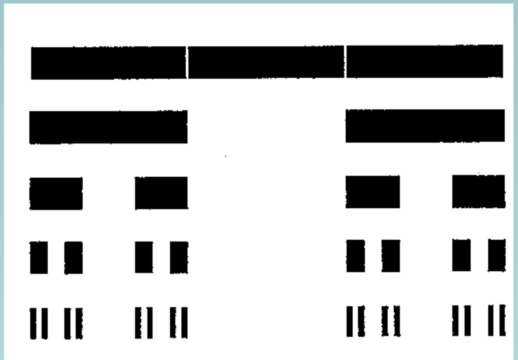






David fractal

Cantor set



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Classification of fractals and summary of fractal rules

1. Formation par voie itération

soit l’extension soit subdivision

2. Autosimilarité

l’observation du même image sous n’importe quelle résolution

3. Types des fractales (en longueur, en surface et en volume)

aérosols et poussières fractales : $0 < D < 1$

périmètres d’un grain ou d’une île,
surfaces planes (mosäiques) : $1 < D < 2$

surfaces rocheuses, rugueuses $D > 2$
agrégats colloïdaux, éponges : $2 < D < 3$

4. Masse volumique n’est pas constant dans l’espace fractale!

conséquence: distributions multimodales de pores/particules souvent observées

5. Dimension fractale reflet le mécanisme de croissance

structures déterministes (régulières) et stochastiques (irrégulières)
on trouve structures différentes ayant la même dimension fractale!

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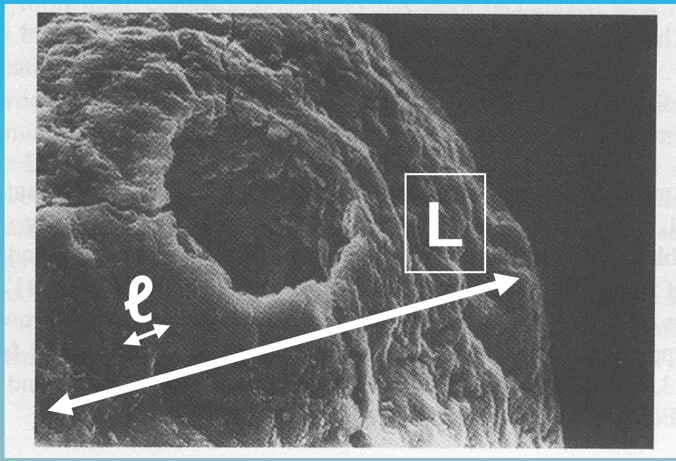
Chap. 4.2 Mesures expérimentales de D_f

$$D = \lim_{\ell \to 0} \frac{\log N^k}{\log (1/\ell)^k} \longrightarrow N(\ell) \sim \ell^{-D}$$



$\varepsilon = \ell/L$

"yardstick"

$$N(\varepsilon) \sim \varepsilon^{-D}$$

Nombre des pixels
carrés
billes
molécules

le but:
$\varepsilon << 1$

Nombre des détails ~ (résolution d'une mesure)$^{-D}$

Stratégie principale:

On cherche a compter le nombre de détails en fonction de la taille du segment ε choisi pour le recouvrement d'une structure complexe

“Standard tiling relations”

Longueur L (périmètre) $= N(\varepsilon)\,\varepsilon \sim \varepsilon^{-D}\,\varepsilon \sim \varepsilon^{1-D}$

Surface A (couche) $= N(\varepsilon)\,\varepsilon^{2} \sim \varepsilon^{-D}\,\varepsilon^{2} \sim \varepsilon^{2-D}$

Volume V (agrégat) $= N(\varepsilon)\,\varepsilon^{3} \sim \varepsilon^{-D}\,\varepsilon^{3} \sim \varepsilon^{3-D}$

grandeur ~ (résolution d’une mesure) $^{\beta\,(D,\,\dots)}$

Power law!

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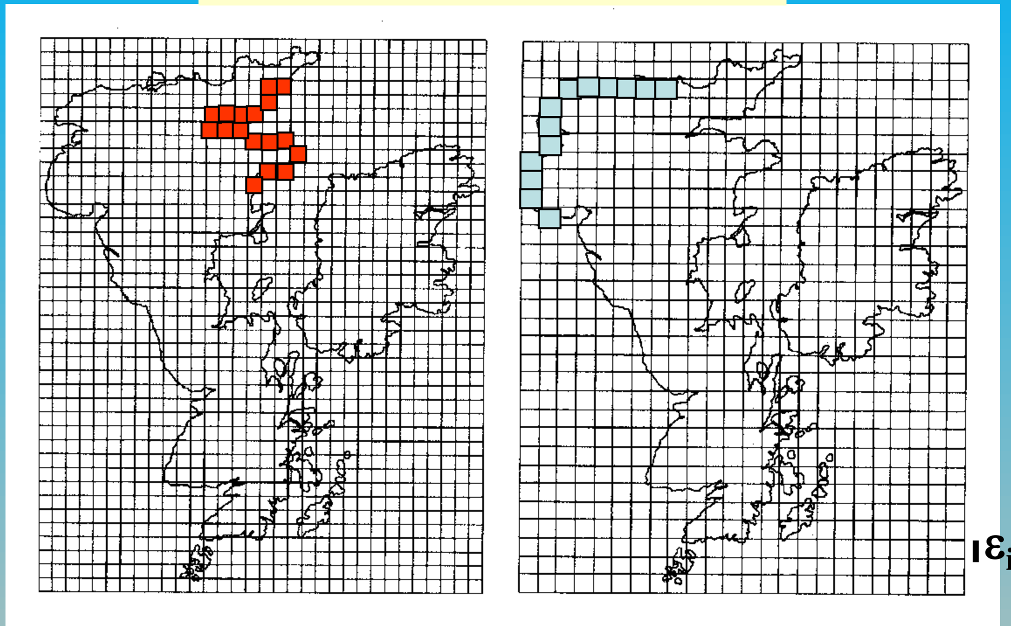
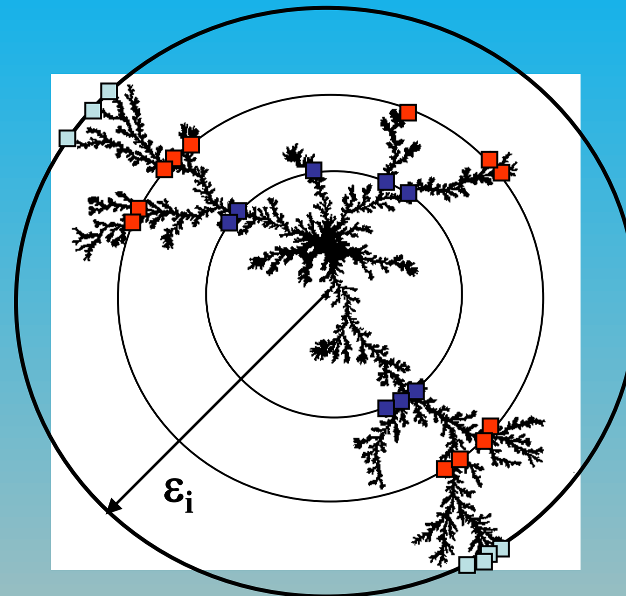
“box counting method”

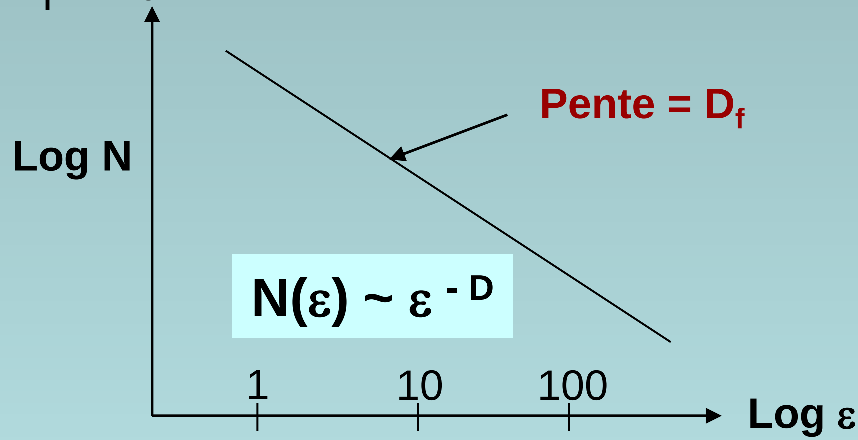


Dimension fractale de la côte littorale de Grande Bretagne $D_f = 1.31$

“sandbox method”



Cluster dendritique de zinc formé en électrolyse, $D_f \sim 1.7$



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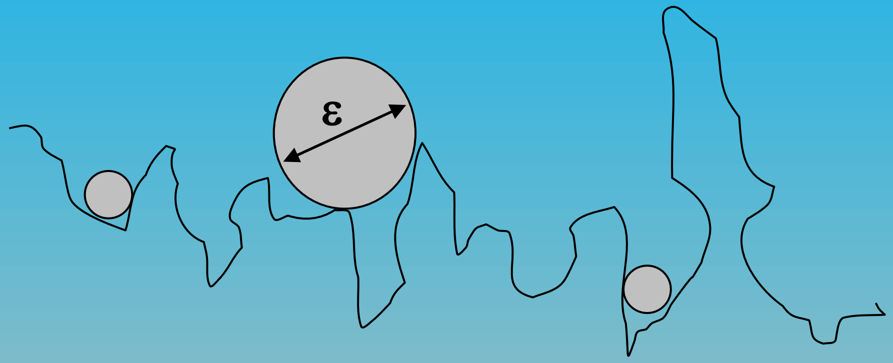
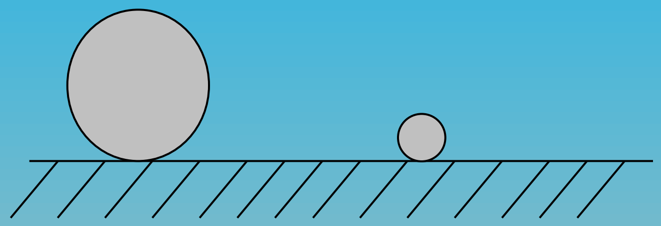
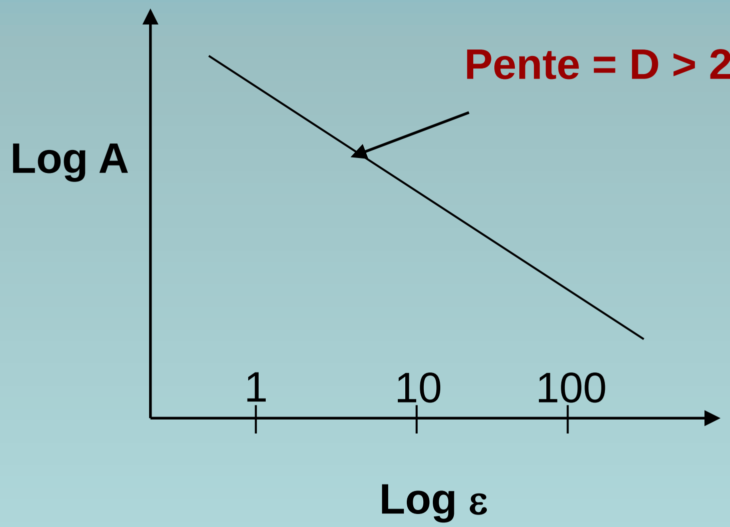
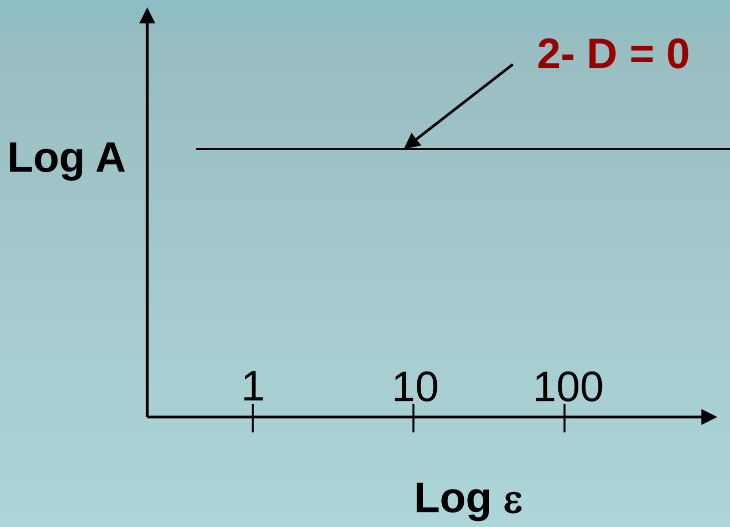
Physisorption des molécules **Surface A = N(ε) ε ^{2} ~ ε $^{2-D}$**









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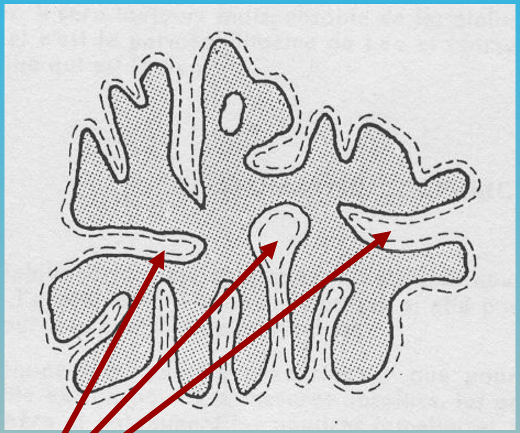
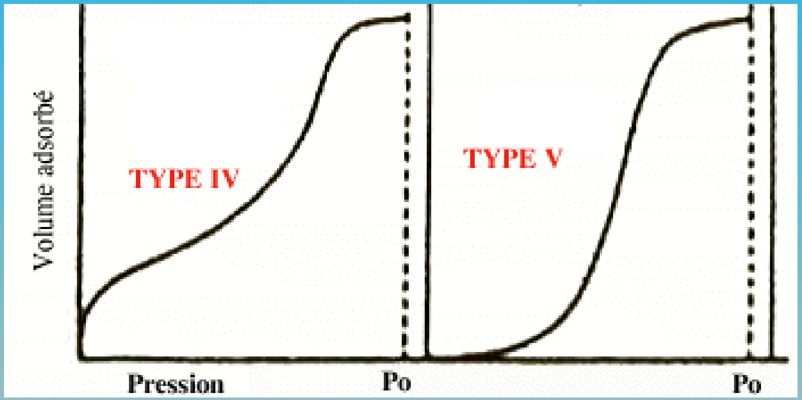
Physisorption de N_2 (BET)

condensation capillaire

Rappel:





Mésoporosité, $2\ nm < R_p < 50\ nm$

$$R_p = -2\gamma V_m / RT \ln(p/p°)$$

$$\left.\begin{array}{l} R_p \sim 1/\ln(p/p°) \\ V = N(\varepsilon)\,\varepsilon^3 \sim \varepsilon^{3-D} \end{array}\right\} \varepsilon = R_p \longrightarrow V \sim R_p^{3-D} \sim [\ln(p/p°)]^{D-3}$$

Autre option: variation de la taille des molécules (ε) appliquées en physisorption

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Mesures SAXS, SANS, LALLS

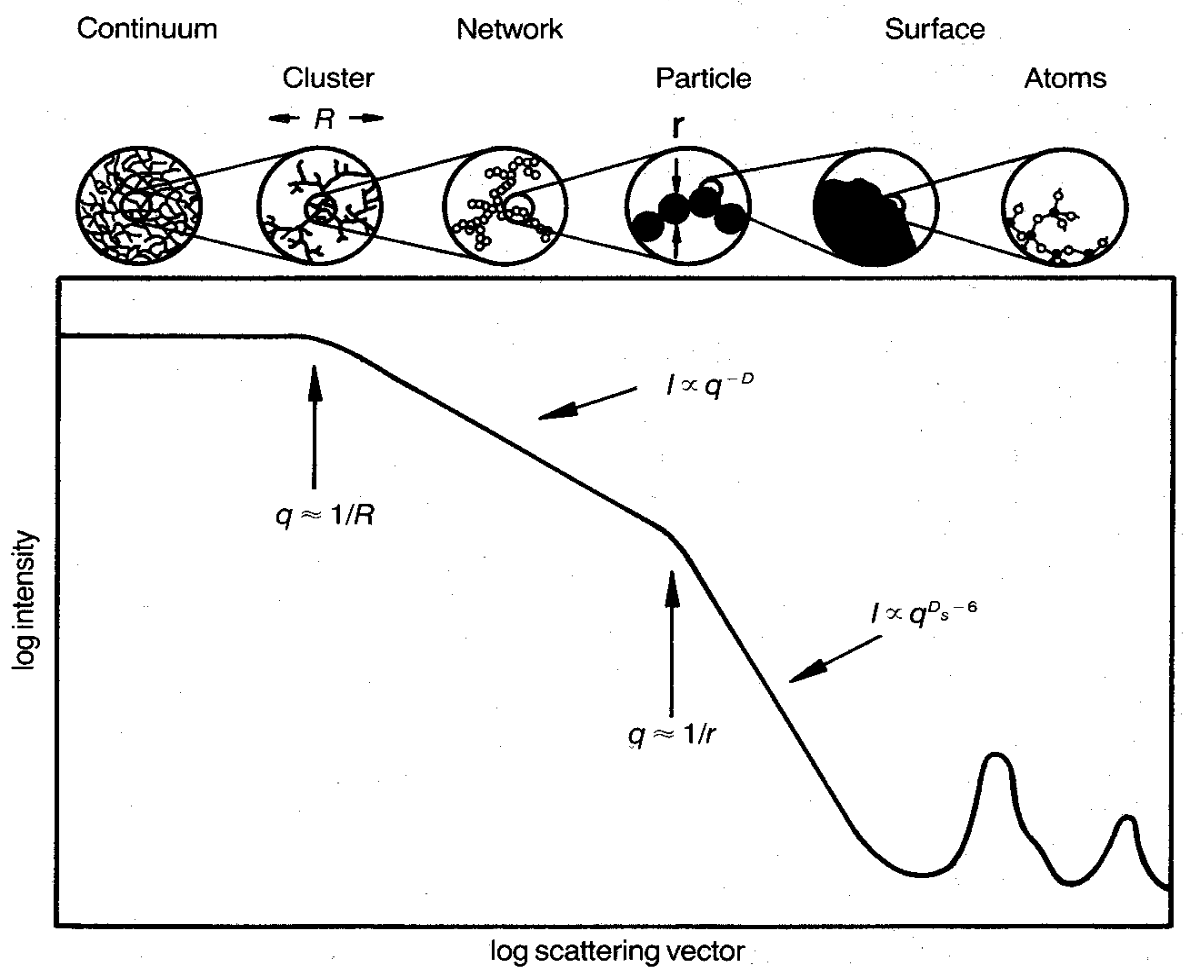
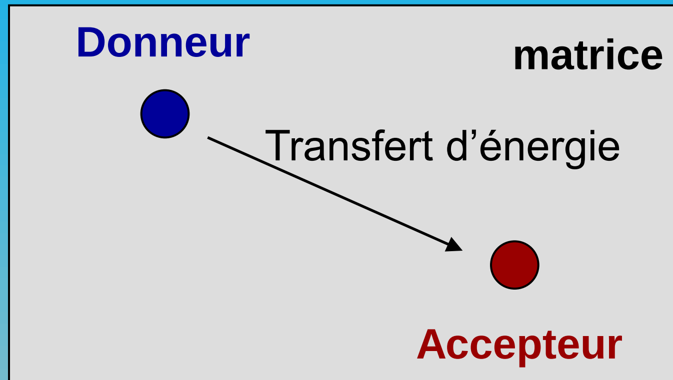


Fig. B2. Small-angle scattering curve for a disordered particle network. All structural features appear in the corresponding regions of scattering vector q. R and r denote a mean cluster and particle size, respectively; exponents D and D_s, determining a power-law decay, are a measure of the morphology of network aggregates and particle surfaces, respectively.

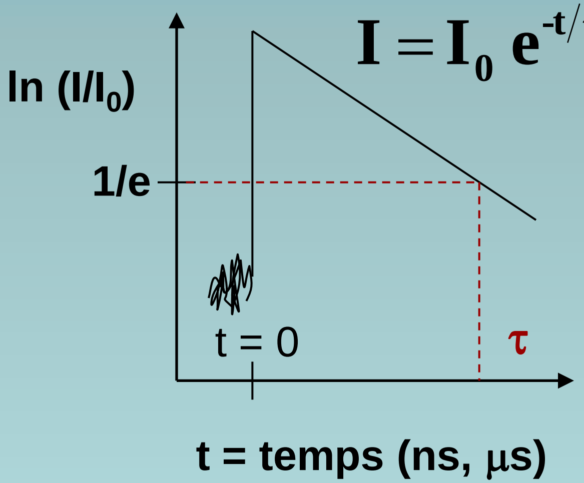
D_f à partir des mesures de fluorescence



soit molécules organiques
soit lanthanides

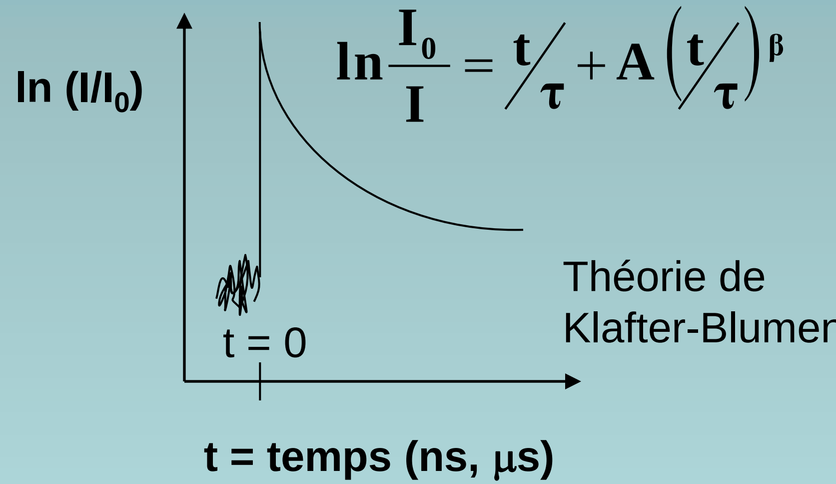
Donneur singulière

$$I = I_0\, e^{-t/\tau}$$



Pair Donneur - Accepteur

$$\ln \frac{I_0}{I} = t/\tau + A\left(t/\tau\right)^{\beta}$$



β = D/s = 0,5 pour le réseau non-fractal avec s = 6
S = 6 implique l'interactions dipôle - dipôle

F I N