

*Chaire de Chimie des Processus Biologiques*  
*Marc Fontecave, Professeur*

**Chimie et défis énergétiques du 21 ème siècle : du soleil aux nouvelles énergies**

**Séminaire du 19 mai 2009, Collège de France**

# **Chimie et conversion photovoltaïque de l'énergie solaire**

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Institut de recherche et développement sur l'énergie  
photovoltaïque (IRDEP)

UMR 7174 CNRS-EDF-ENSCP





L'IRDEP est localisée à Chatou sur l'un des trois sites d'EDF R&D

# Plan

Contexte général

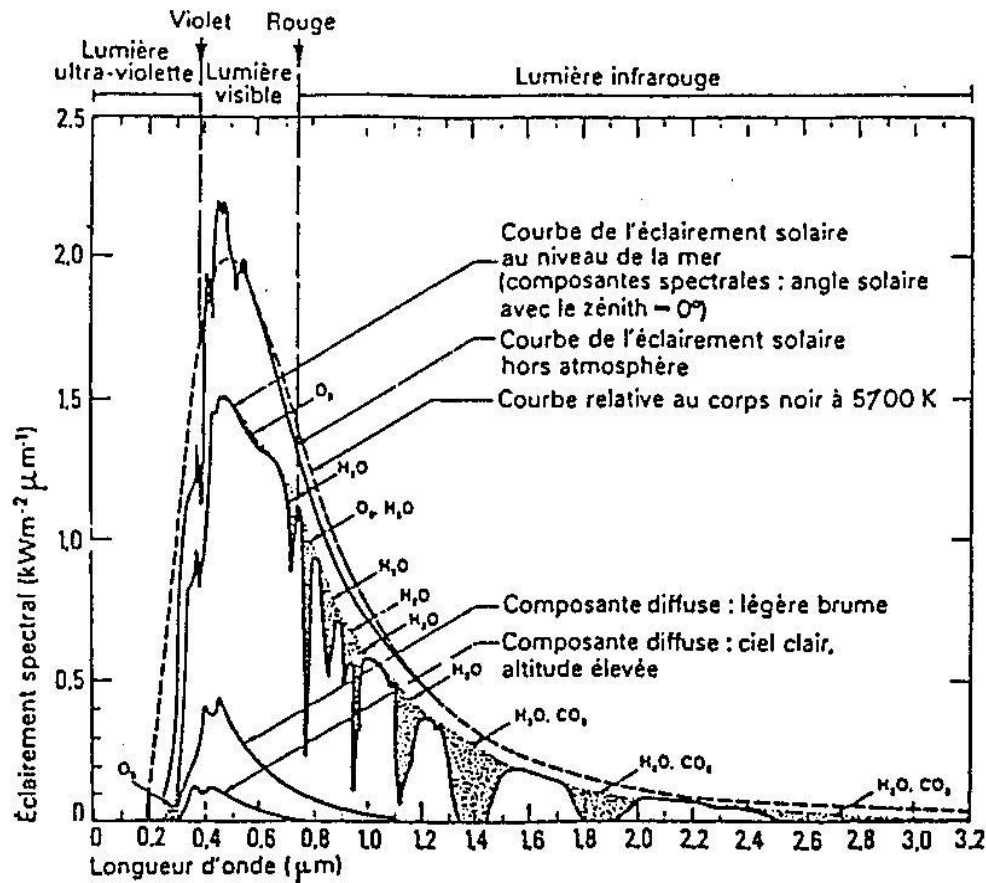
La filière silicium

Les filières couches minces

Le photovoltaïque nanostructuré

Les très hauts rendements

# Le rayonnement solaire



Puissance incidente hors atmosphere:  $1350 \text{ W/m}^2$

En un an :  $10,6 \text{ MWh/m}^2$  soit près d'une tonne équivalent pétrole

Wh/m<sup>2</sup>

1850-1950

1750-1850

1650-1750

1550-1650

1450-1550

1350-1450

1250-1350

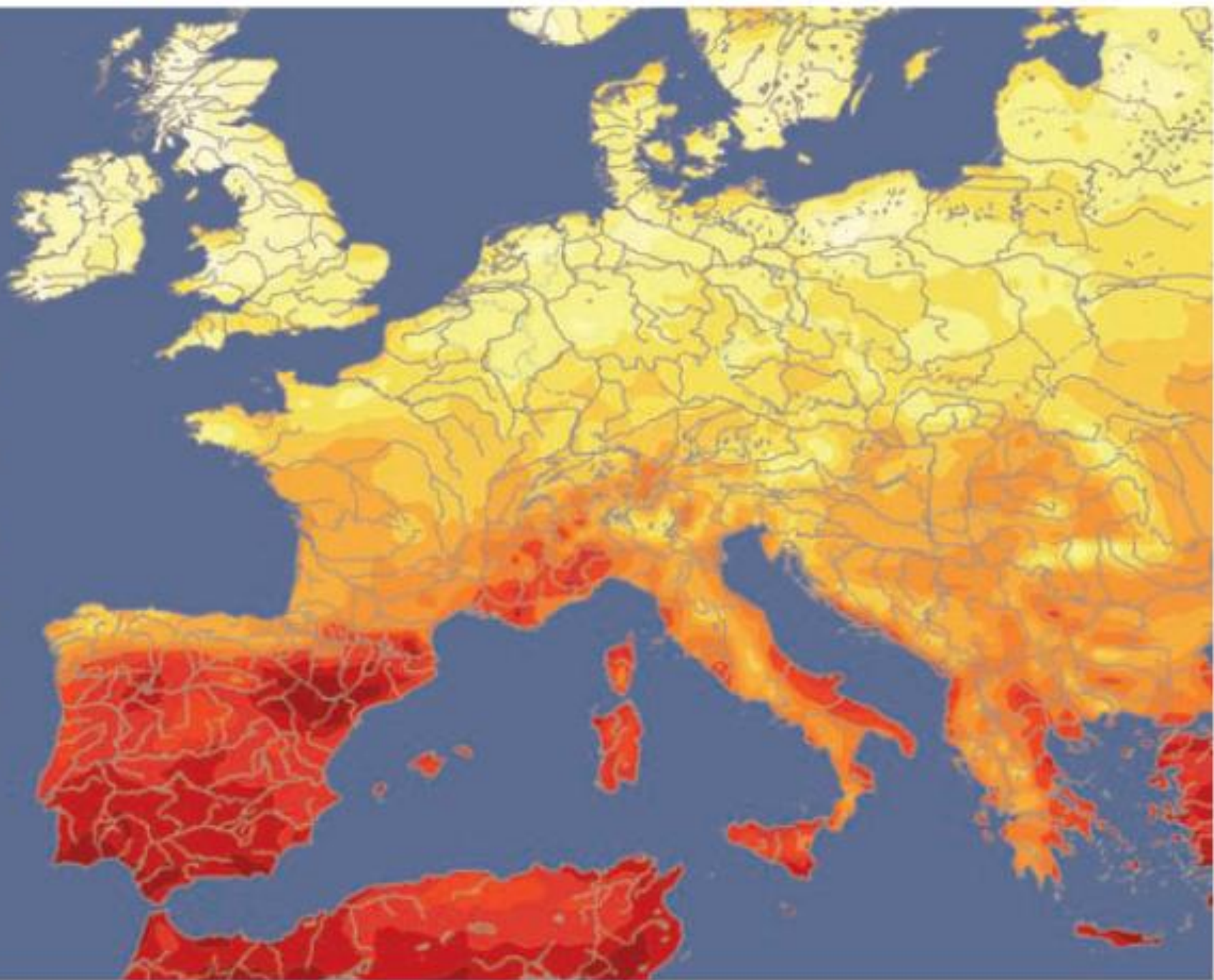
1150-1250

1050-1150

950-1050

850-950

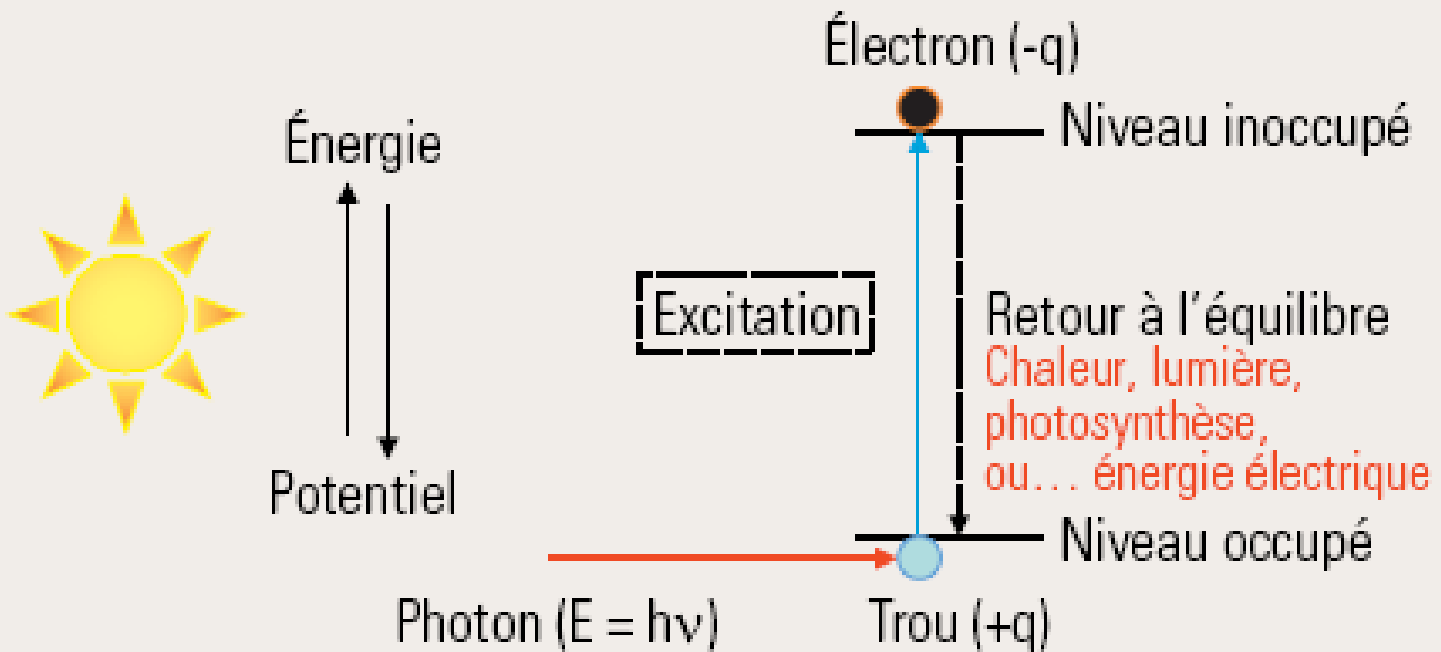
750-850



# Contexte

- Energie solaire incidente (AM1,5) : 1000 W/m<sup>2</sup>
- Moyenne en France : 1300 kWh/m<sup>2</sup>/an
- Ressource (@10%) : 130 kWh/m<sup>2</sup>/an
- Equivalent 550 TWh/an : 5000 km<sup>2</sup>
- Infrastructures : 30000 km<sup>2</sup>

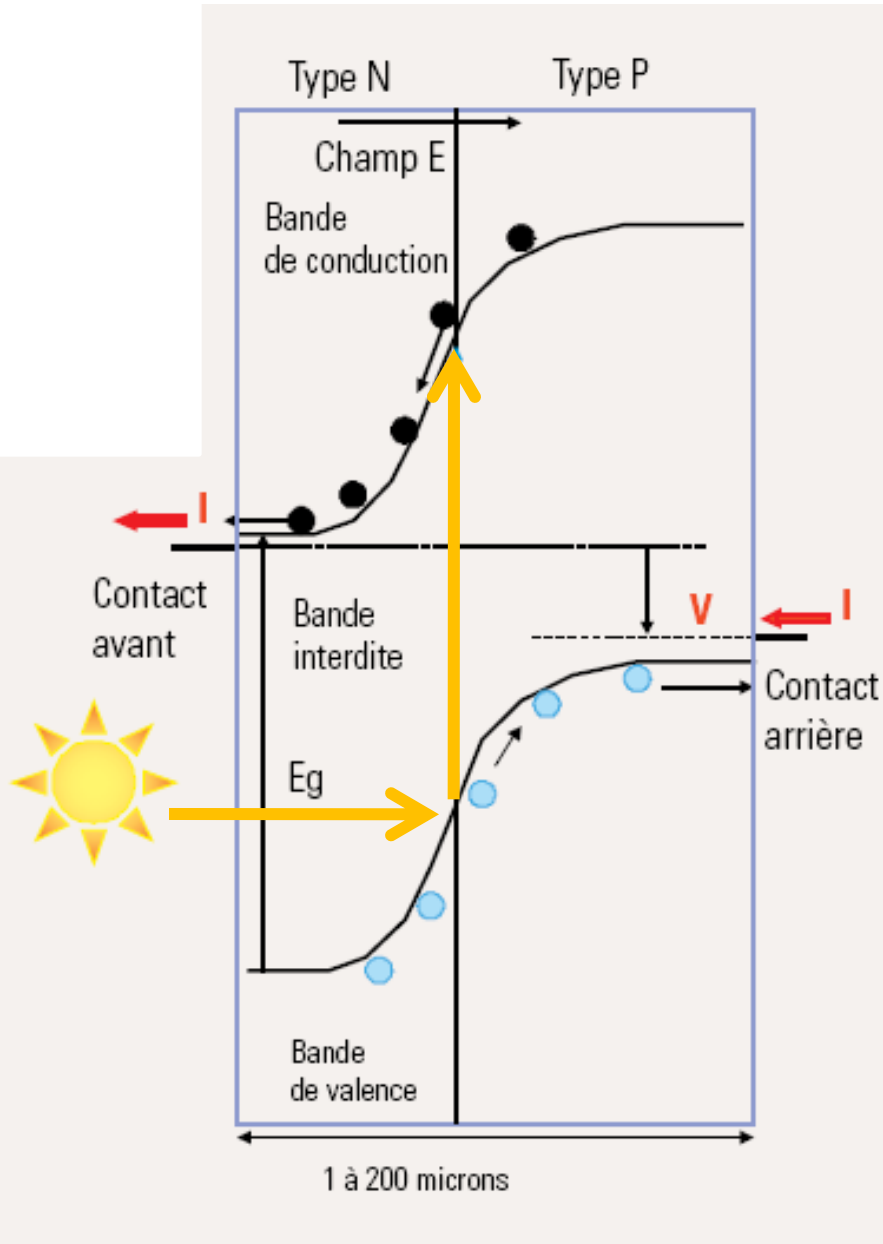
**Ressource énergétique considérable**



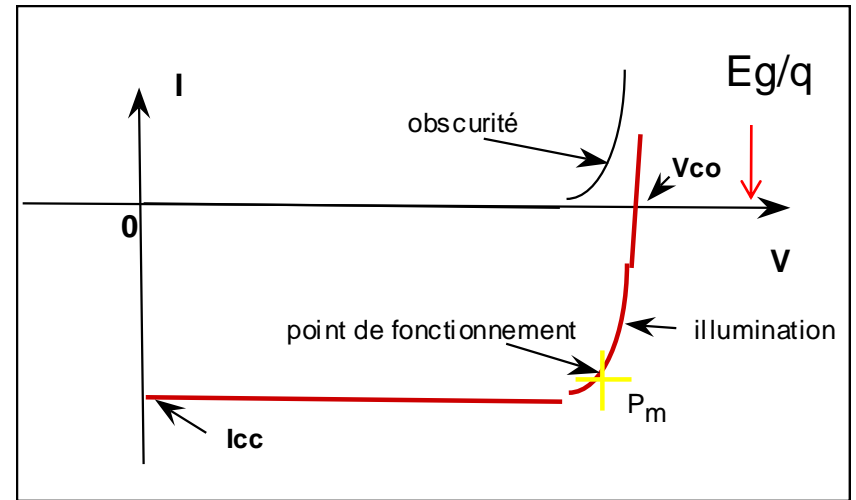
***FIGURE 5***

**Processus d'adsorption de la lumière dans un matériau.**

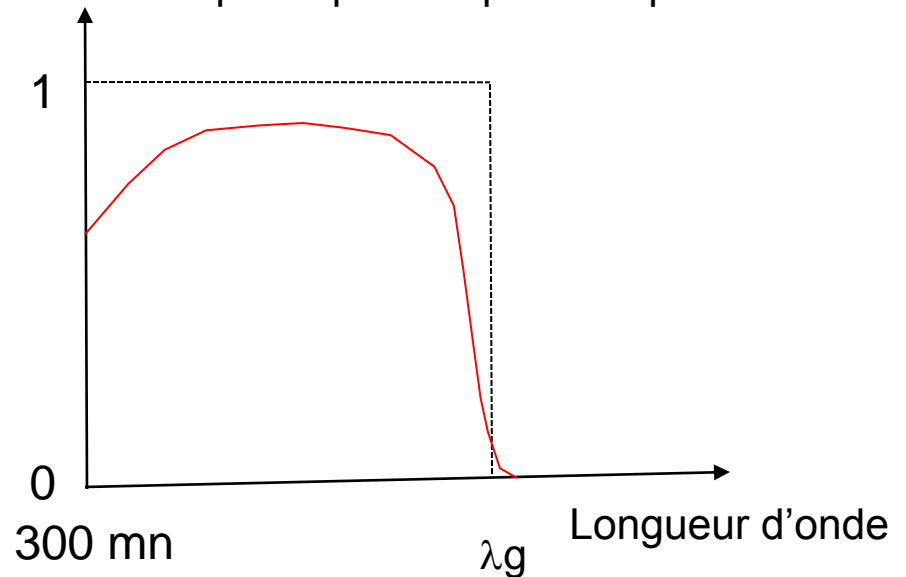
Si dopé P (B)    Si dopé N (P)



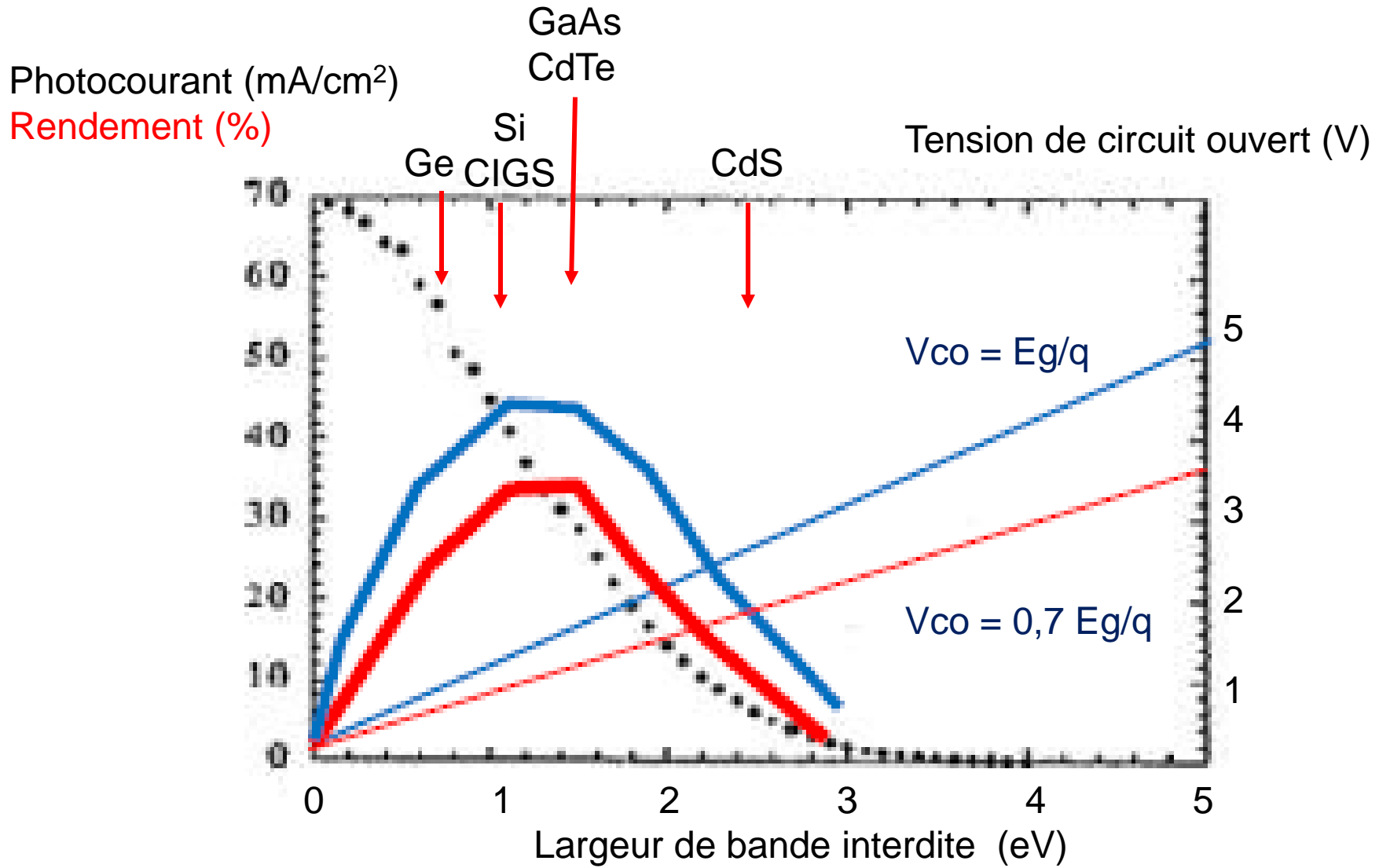
$$I = I_0 [\exp (qV/nkT) - 1] - I_L$$



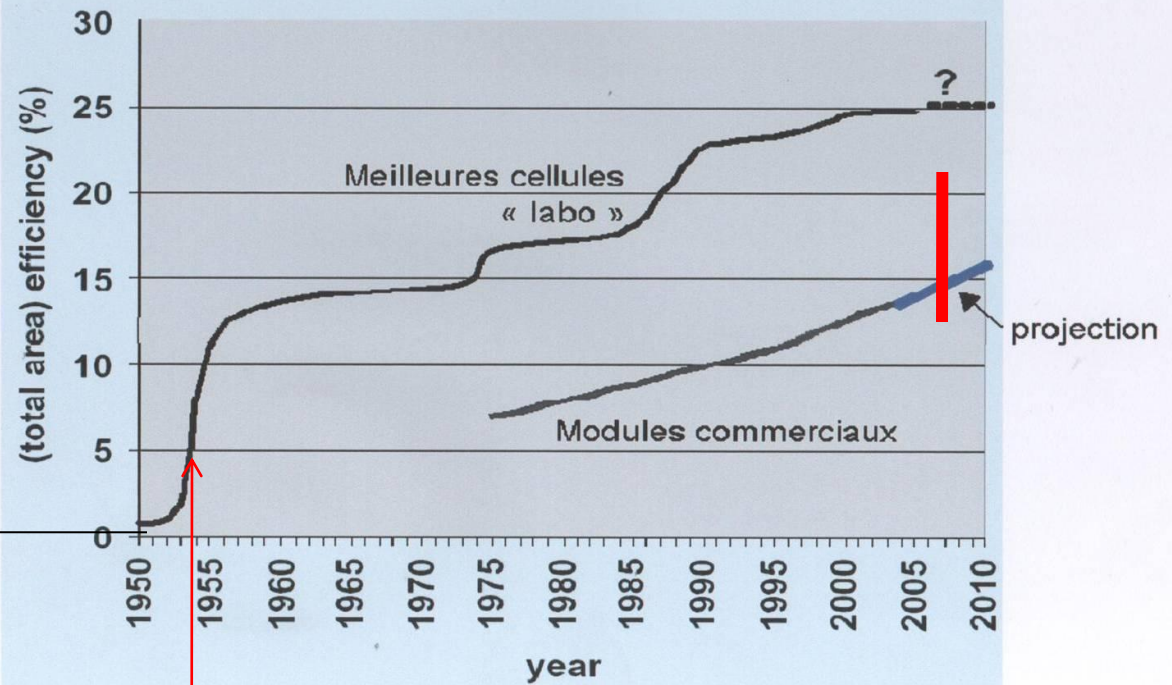
Rendement quantique =  $e^-$  produit / photon







# Histoire du photovoltaïque



1839

E. Becquerel  
Le découvreur

1877

W.G. Adams  
& R.E. Day

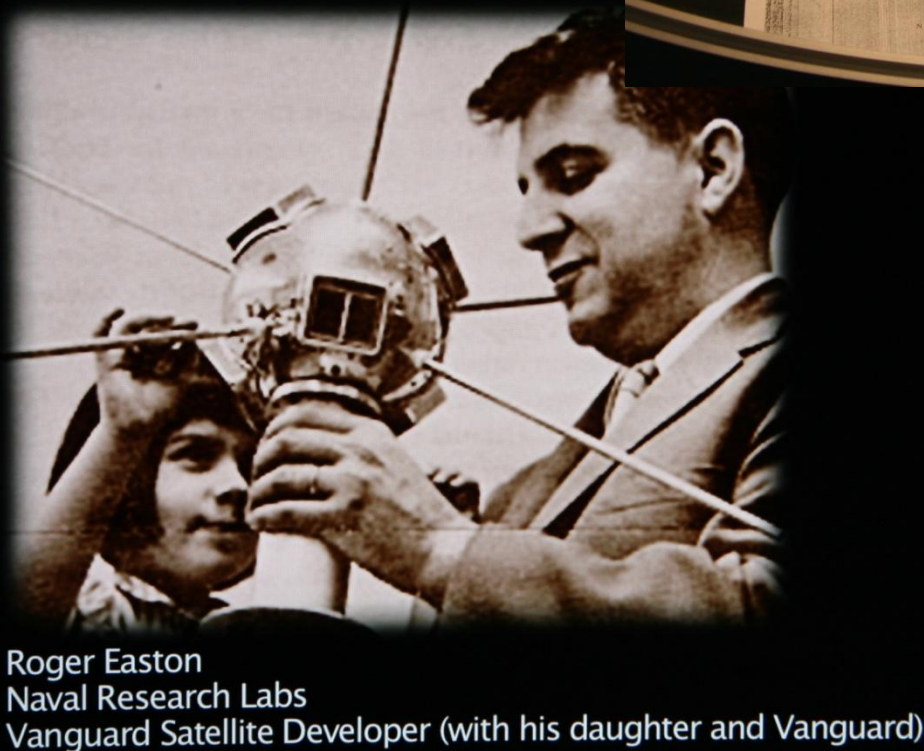
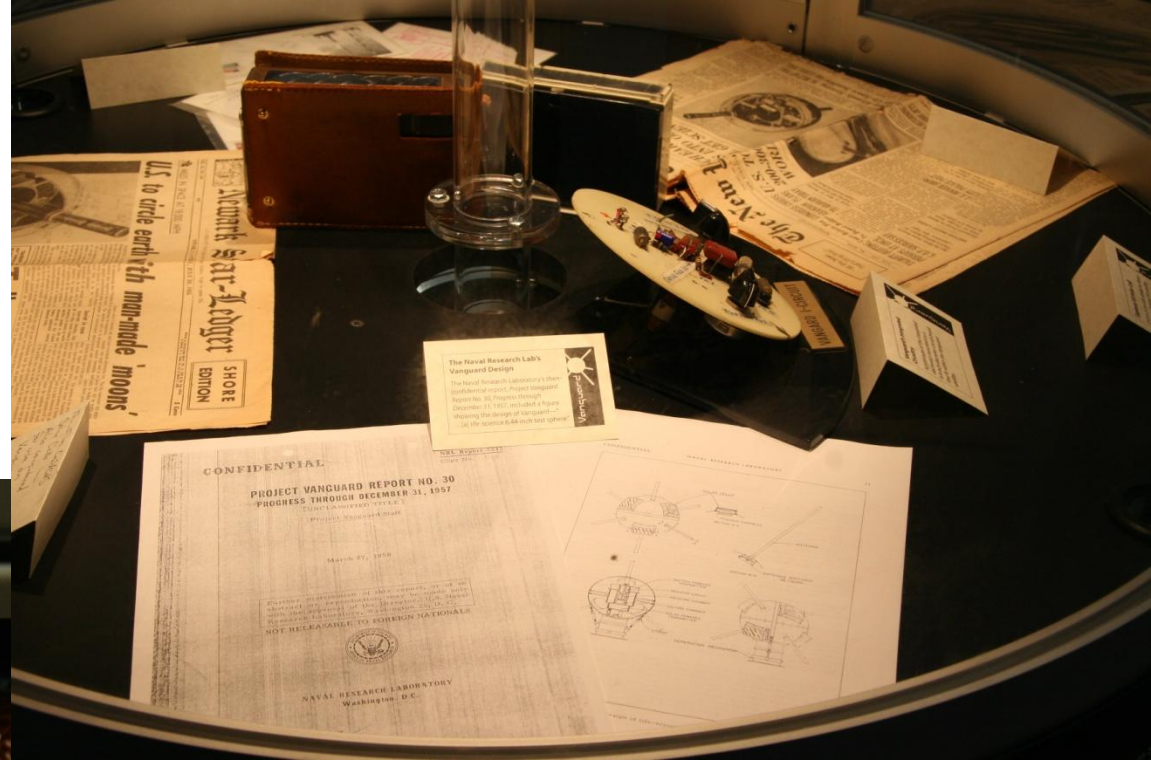
Cellules  
Se 1%

Chapin & Fuller  
& Person  
Si(6%)

Source : J.C. Muller

Premier Satellite  
Alimenté par des cellules  
photovoltaïques

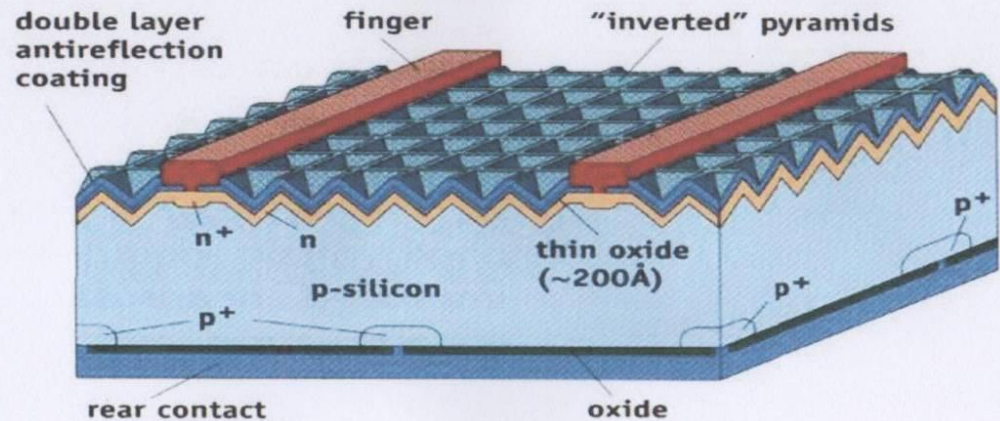
Vanguard, USA, 1958



Roger Easton  
Naval Research Labs  
Vanguard Satellite Developer (with his daughter and Vanguard)

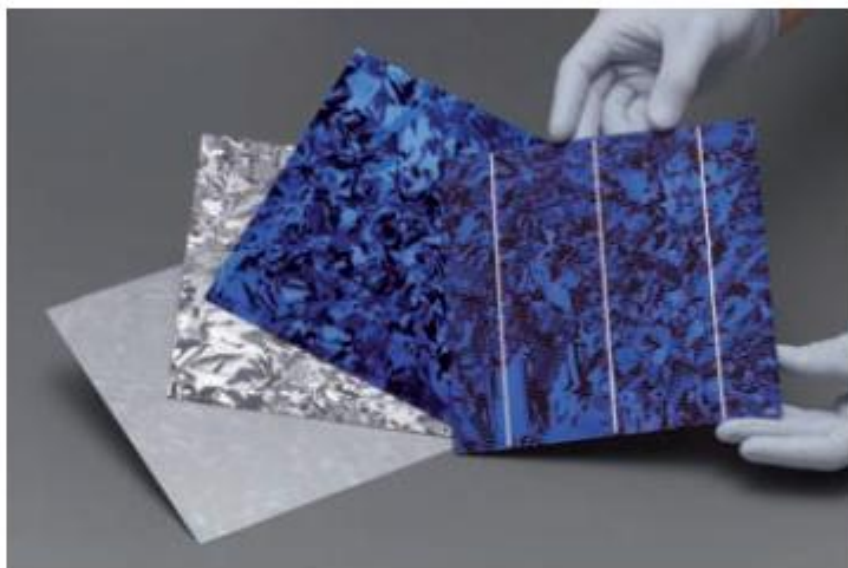
Photos:  
J. Wanegue

# Cellule au silicium de rendement record

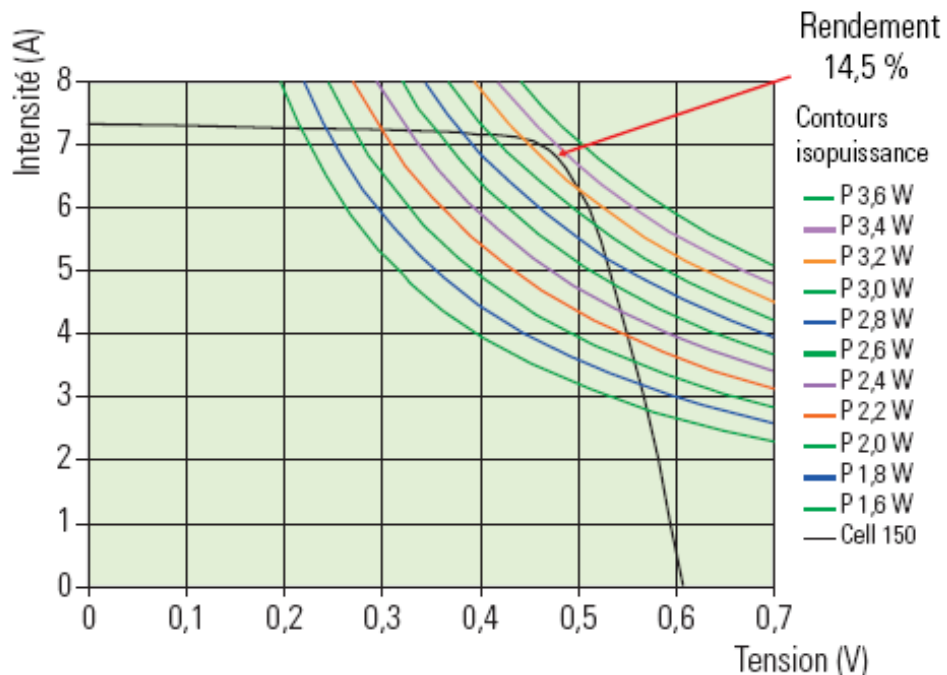


$$I_{cc} = 42,2 \text{ mA/cm}^2 \quad ; \quad V_{co} = 0.706 \text{ Volt} \quad ; \quad \eta_p = 24,7 \%$$

*Cellule PEARL M. Green et al UNSW (Australie)*



**FIGURE 8**  
**Cellule photovoltaïque silicium 20 cm × 20 cm.**  
**Rendement de conversion 14,75 %**  
 De gauche à droite : plaque Si après découpe,  
 après texturation, après formation de la jonction  
 et dépôt du traitement anti-réfléchissant et cellule  
 finie.  
 © CEA, plate-forme RESTAURE cofinancée  
 par l'ADEME.



**FIGURE 7**  
**Caractéristique courant-tension**  
**d'une cellule solaire commerciale**  
**au silicium polycristallin**  
 (15 cm x 15 cm de 0,2 mm d'épaisseur)  
 sous éclairage solaire normalisé 1 000 W/m<sup>2</sup>.  
 © Photowatt International S.A.

a)



b)



c)



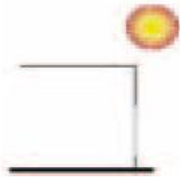


*Parc solaire  
de 10 MWc installé  
à Pocking (Allemagne)  
capable d'alimenter  
3 300 maisons  
en électricité.*

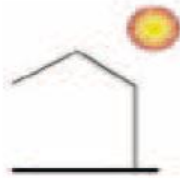
*© www.martin-bucher.de,  
Stuttgart/Germany*

**1 MWc → 100 m x 100 m → 1.3 GWh/an**

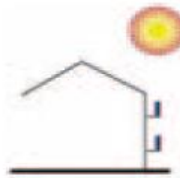
# L'intégration au bâtiment



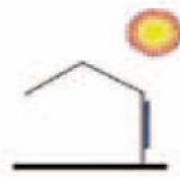
Pose en allèges



Pose en verrière sans protection arrière



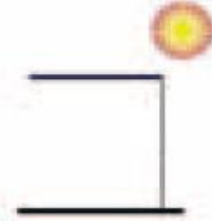
Pose en garde-corps de fenêtre, de balcon ou de terrasse



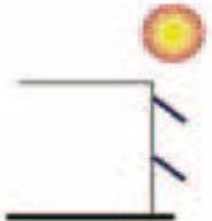
Pose en bardages, mur rideau



Pose en toiture inclinée (tuiles, ardoises,...)



Pose en toiture terrasse (membrane étanche)

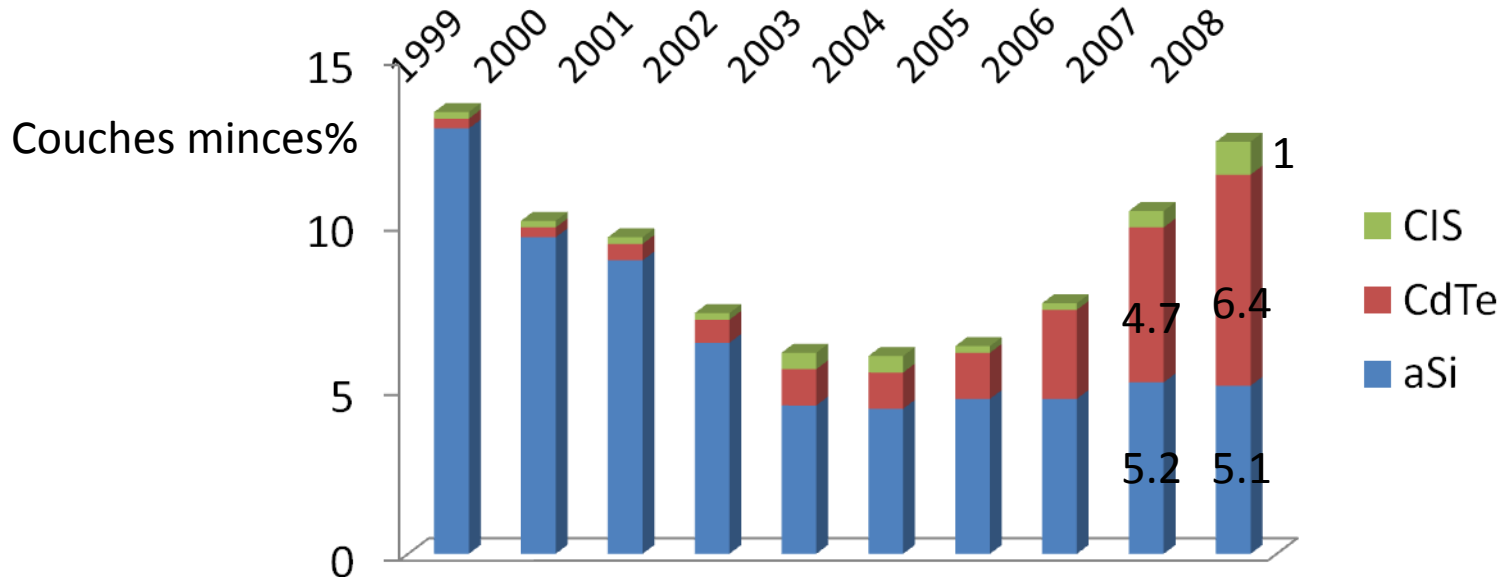
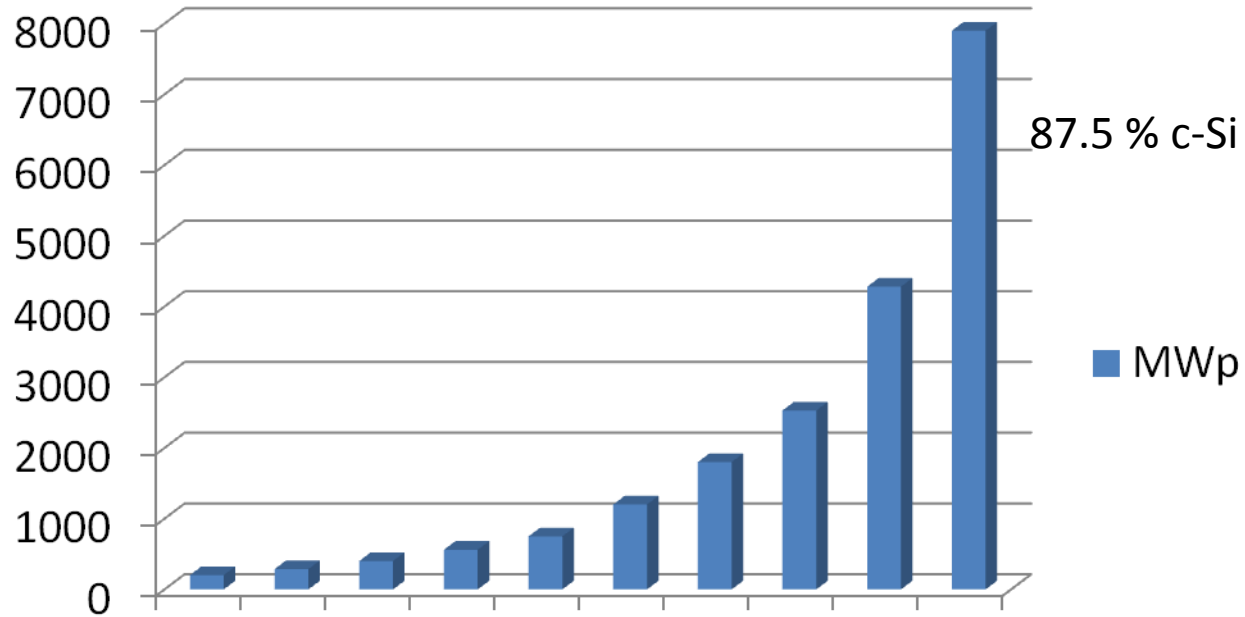


Pose en brise soleil



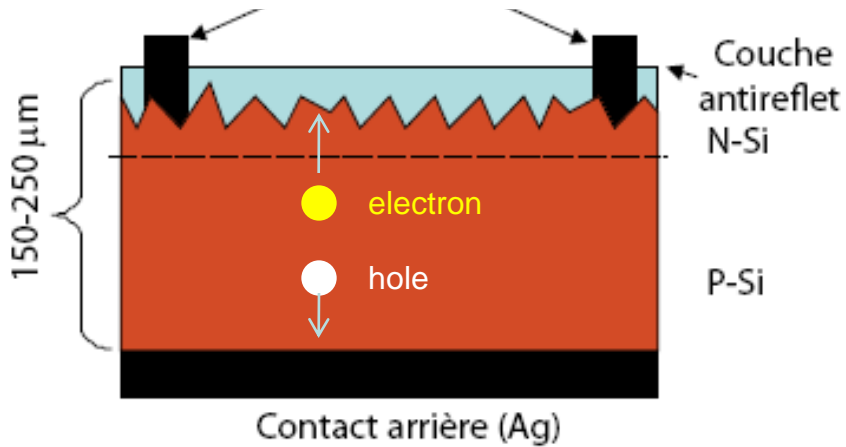


# Production mondiale et répartition entre les filières

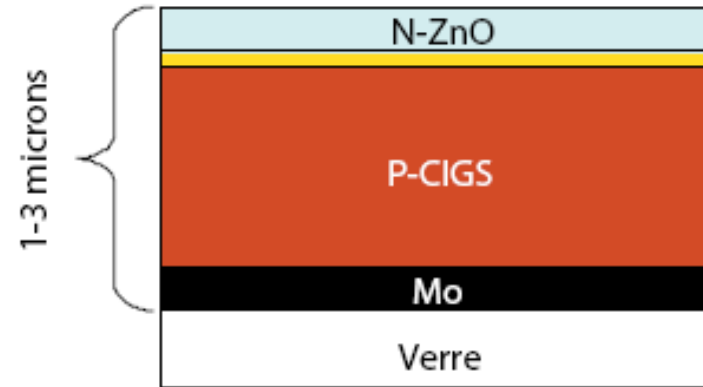




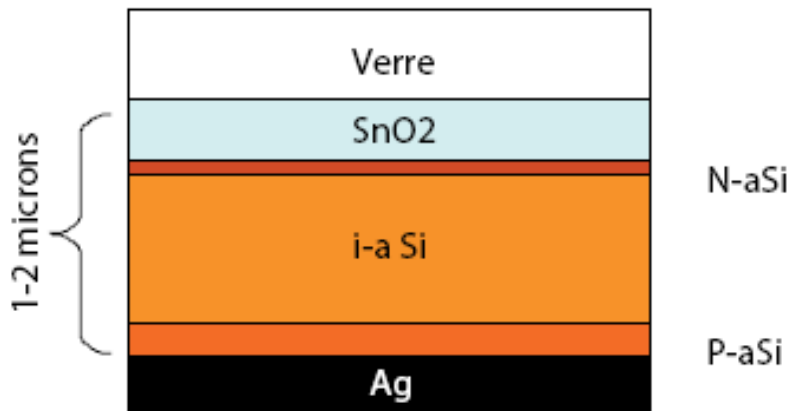
Cristalline silicon (cSi)



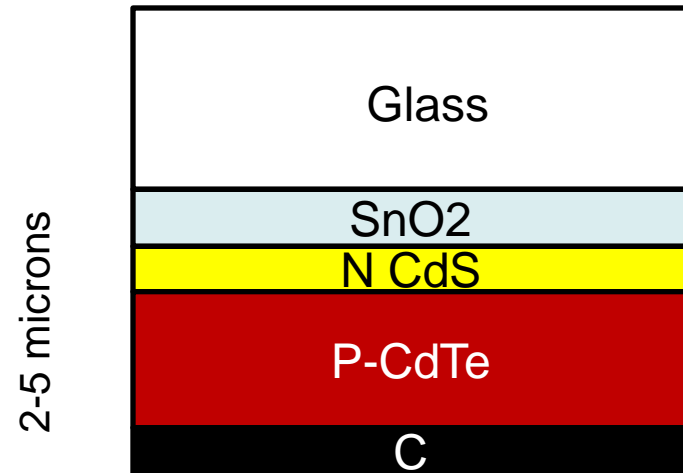
Copper Indium gallium diselenide (CIGS)



Amorphous silicon (aSi)



Cadmium telluride (CdTe)

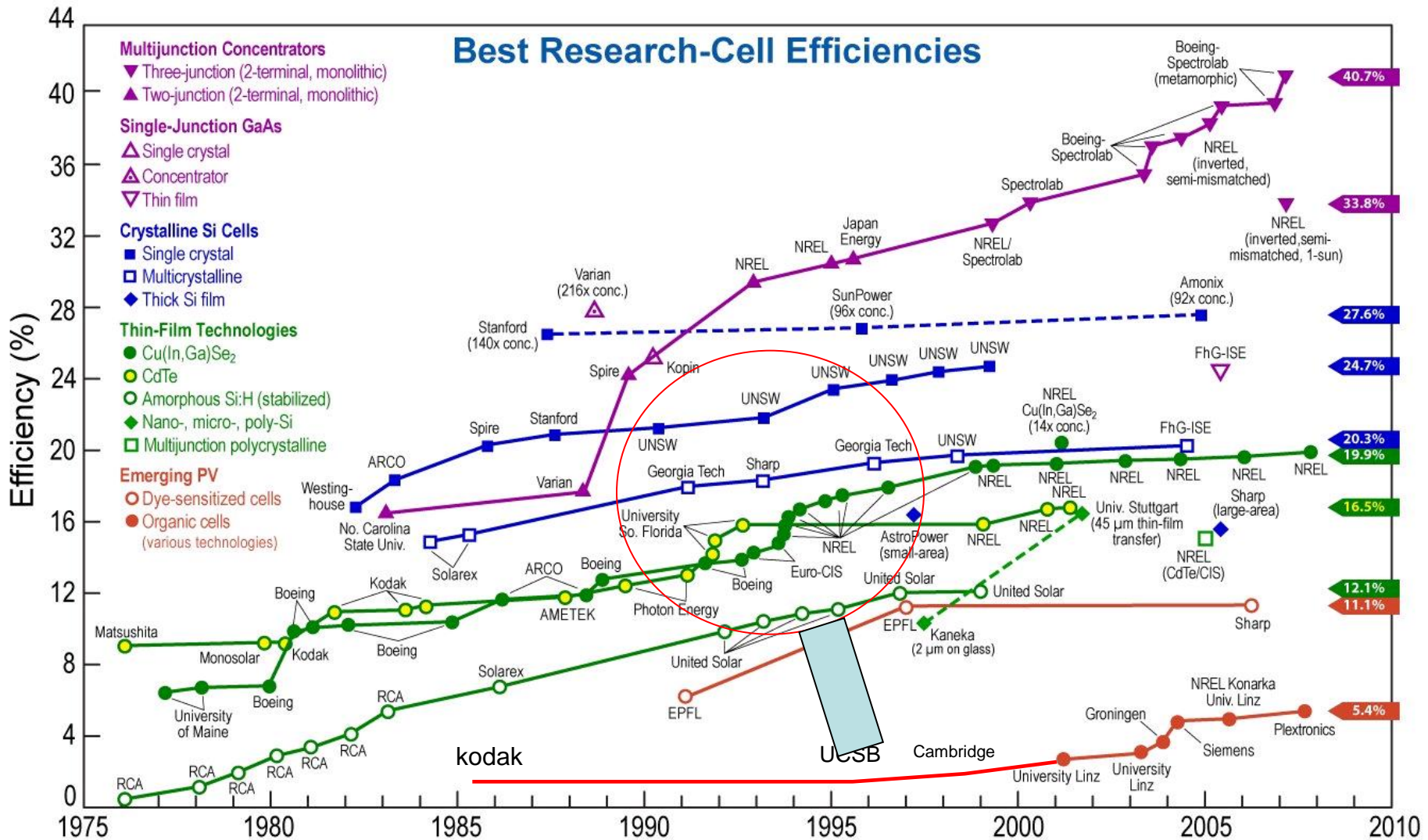


La maison Zen (Zero Energy Net) in Chambery of Alain Ricaud  
Positive energy house in France <http://www.cythelia.fr>

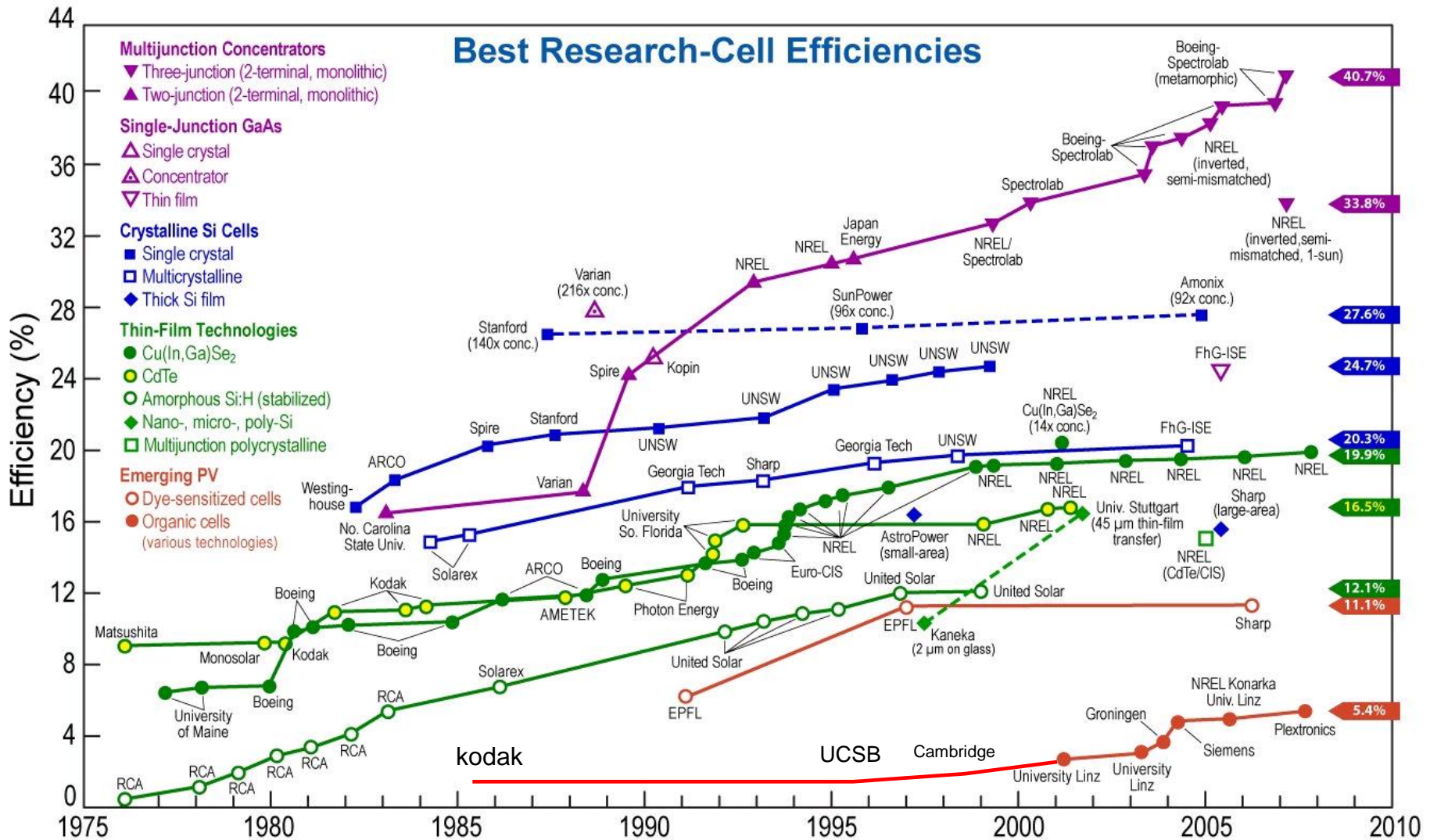


PV System CIS (Sulfurcell) 13.5 kWp 12 000 kWh/year  
for 9000 kWh/year consumption

# Les différentes filières photovoltaïques



# Les différentes filières photovoltaïques



# Place de la chimie

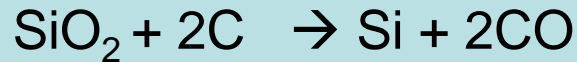
- Le « photovoltaïque » est considéré comme une branche de la physique et de l'électronique
- La chimie n'est pas considérée comme un « acteur » majeur de la chaîne de production et d'innovation :
  - Fourniture de produits chimiques
  - Procédés chimiques
- **Les choses changent rapidement :**

La chimie devient un acteur de premier plan :  
***Matériaux, procédés, concepts***

# Silicium cristallin

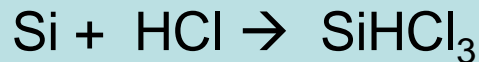
*Matériau massif*

-grade métallurgique (99%, >10 000 ppm, 1700°C) :



- grade électronique(1 ppm)

Dissolution & distillation (250°C)



Craquage réducteur par CVD en présence d'H<sub>2</sub> à 1000°C



*Wafers*

-Recristallisation des lingots 1450°C ((up to 450 kg) (dopage B,

- Découpe, décapage, texturation

*cellules*

-traitement de diffusion ( POCl<sub>3</sub>) conversion type n

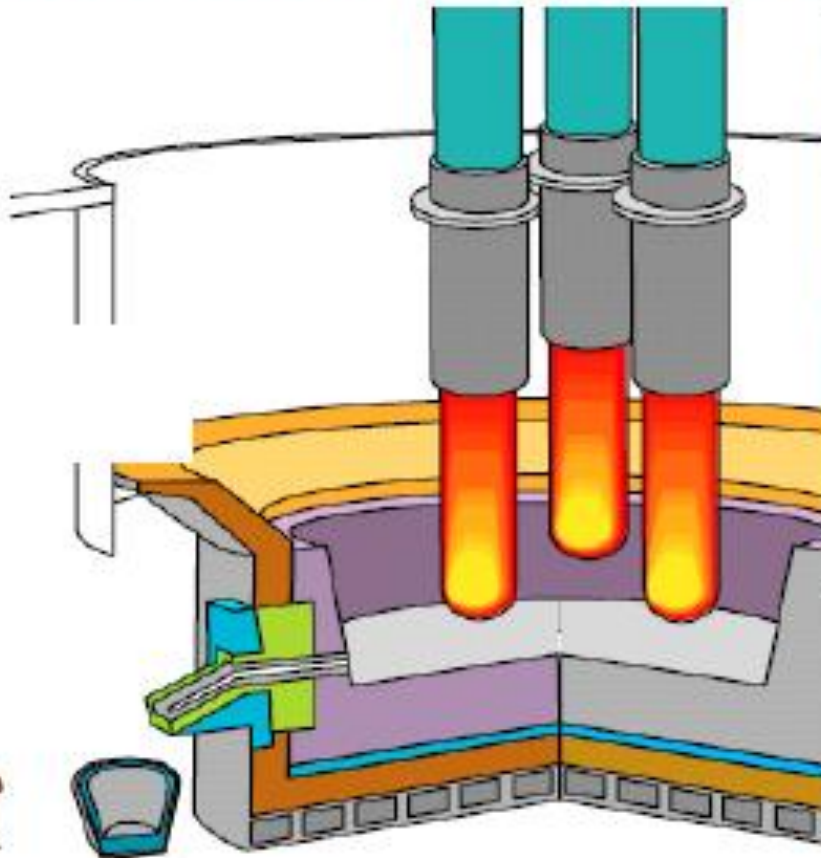
-Contacts (sérigraphie)

# Solar Grade Silicon: show stopper or infinite source

Jan Bultman & Bart Geerligs



## Industrial production of metallurgical-Si (since 1905)



**40,000 MT/y production facility**  
**Worldwide > 1,000,000 MT/y**



# Challenges

## Production directe de silicium pour le photovoltaïque

Purification plasma Si (élimination du bore)

Utilisation de la biomasse :  $\text{SiO}_2$  à partir de paille de riz + carbone

*Peu d'impuretés* ↓

PV quality Si + pas d'émission de  $\text{CO}_2$

Fabrication de Si par voie électrolytique

$\text{SiO}_2 + 4 e \rightarrow \text{Si} + 2 \text{O}(-\text{II})$  en milieux sels fondus

Voie « vertes »

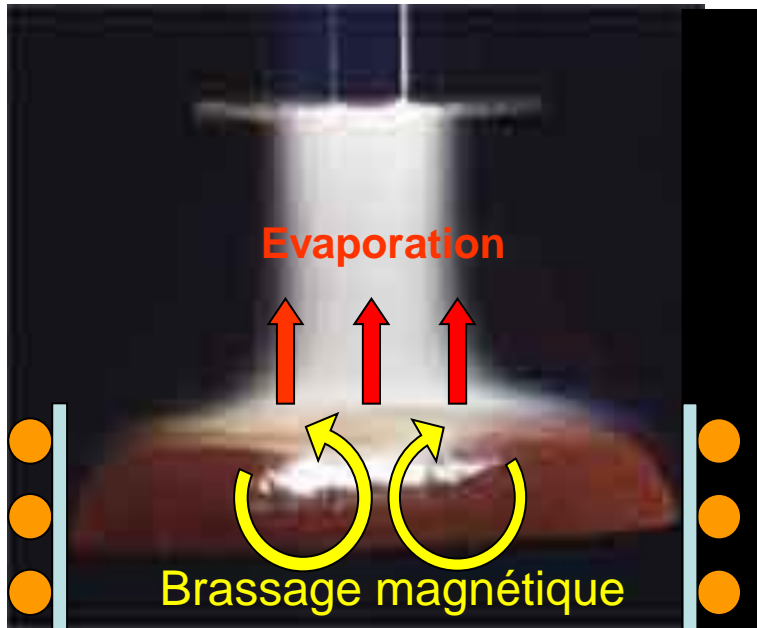
## Cellules

Méthodes d'élaboration couches minces

Challenges matériaux: interaction défauts-impuretés, passivation

# Purification du silicium par Plasma

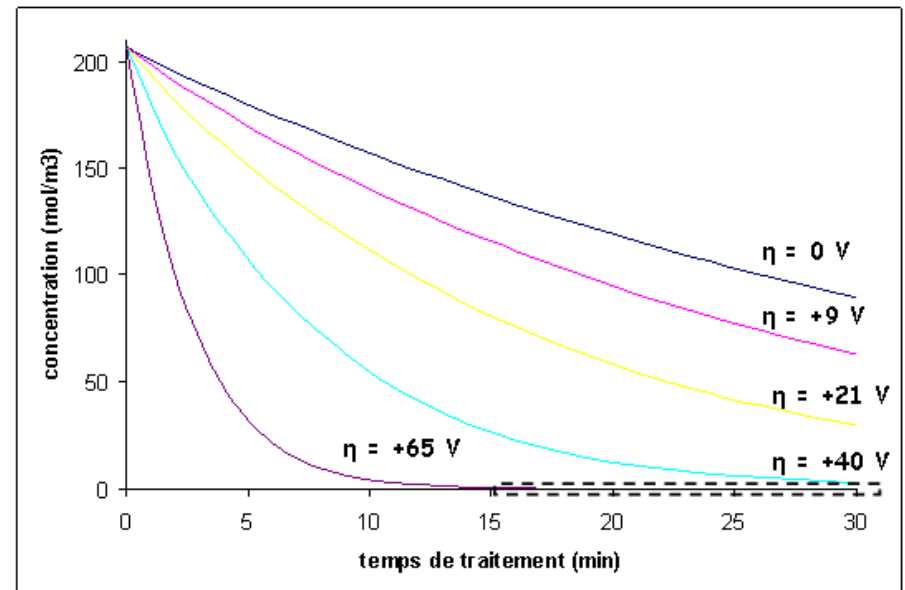
J. Amouroux, D. Morvan Chimie-paristech et UPMC



Innovation récente  
Influence d'un potentiel appliqué

Purification de zone par plasma  
Ar / 1% H<sub>2</sub> / 0.1% O<sub>2</sub> (6 passages 60 cm/h)

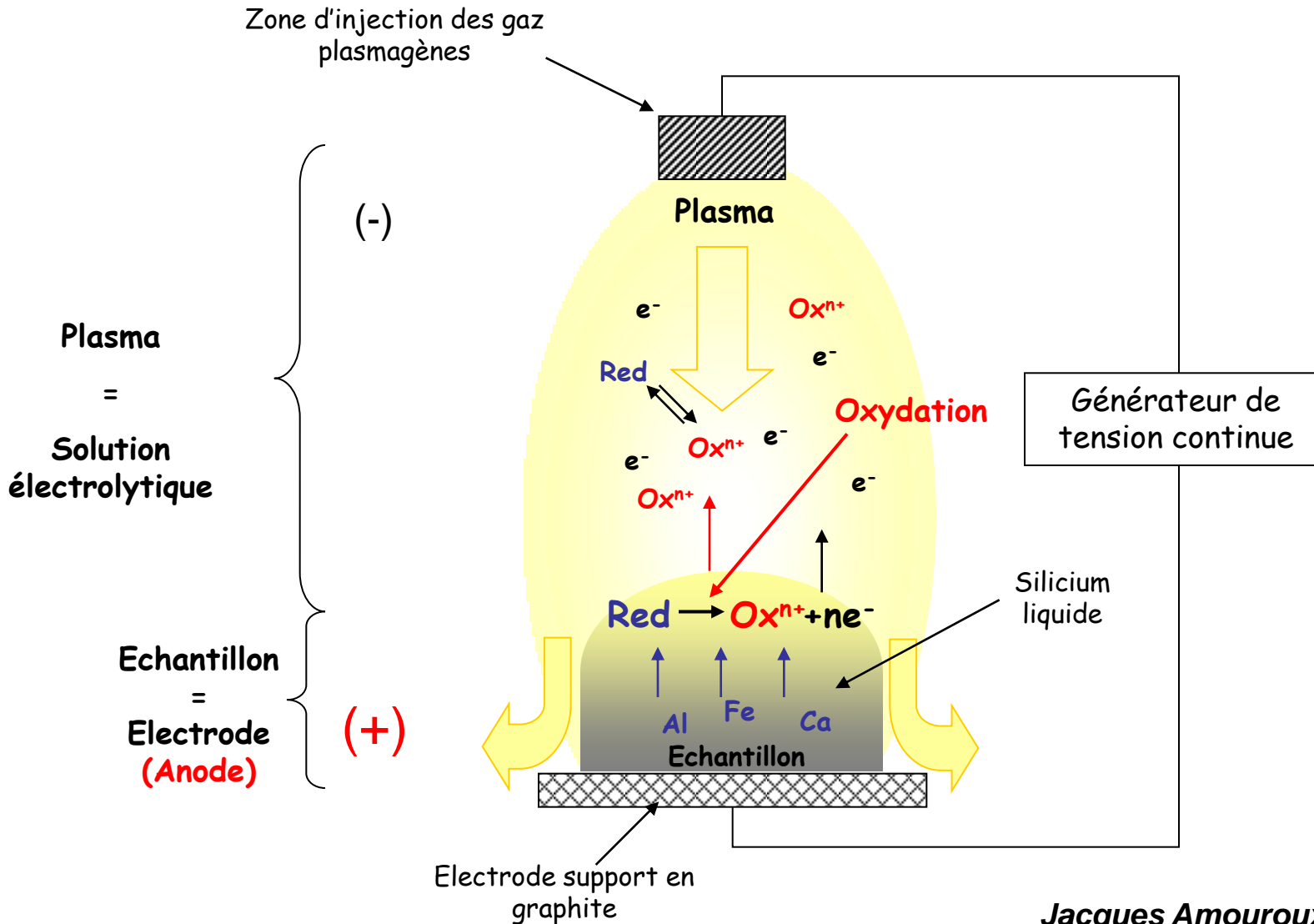
Impureté	Avant traitement (ppmw)	Après traitement (ppmw)
Al	2800	0.0005
B	20	0.0049
Ca	2100	0.002
Fe	3780	<0.8



**Model results : Temperature field**

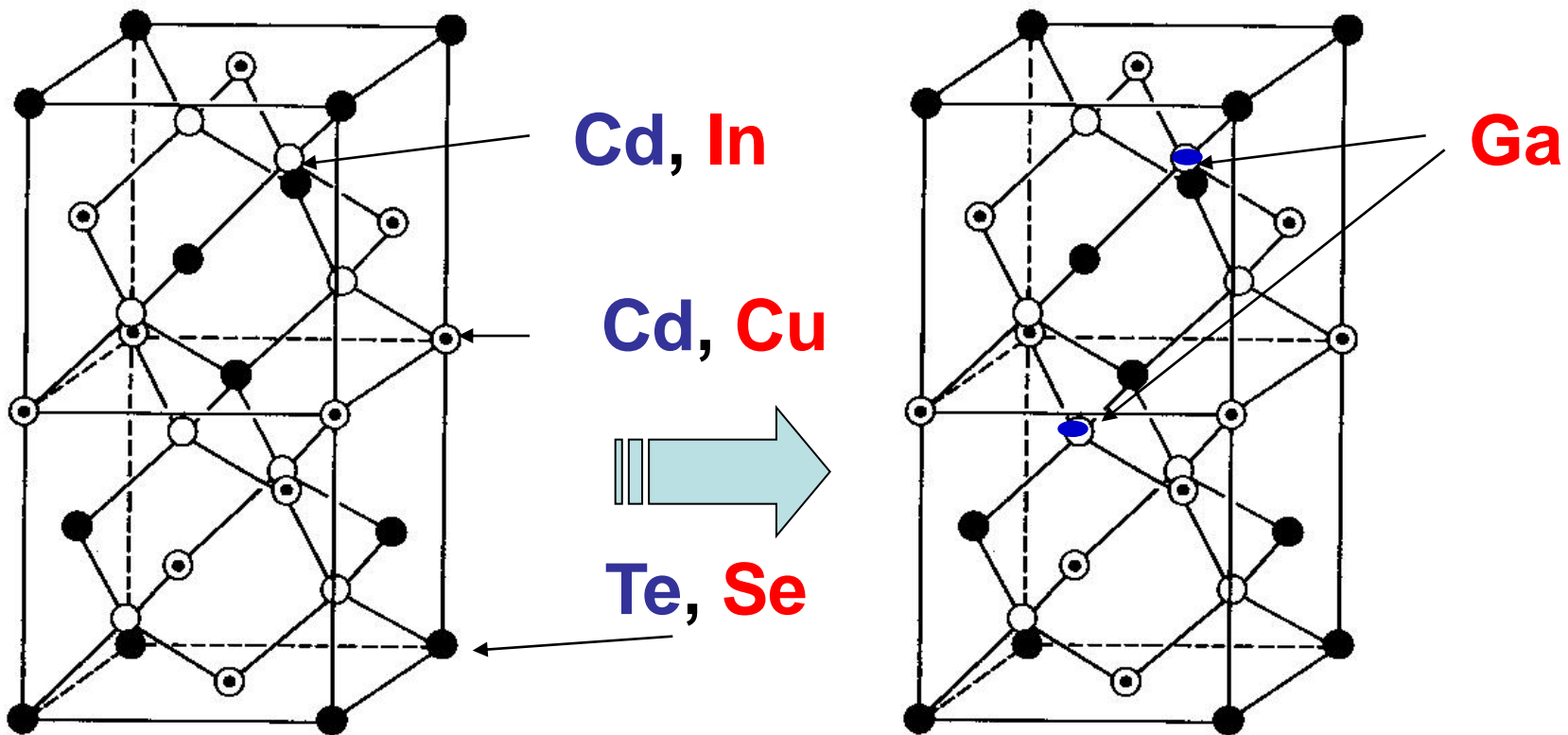
# MECANISME ELECTROCHIMIQUE D'EXTRACTION DES IMPURETES A L'INTERFACE PLASMA - SILICIUM

SILICIUM = ANODE DU CIRCUIT



# Les cellules solaires à base de CIS

**IV (Si) --→ III-V (GaAs) → II-VI (CdTe) → I-III-VI<sub>2</sub> (CuInSe<sub>2</sub> « CIS »)**



**CdTe 1.5 eV**

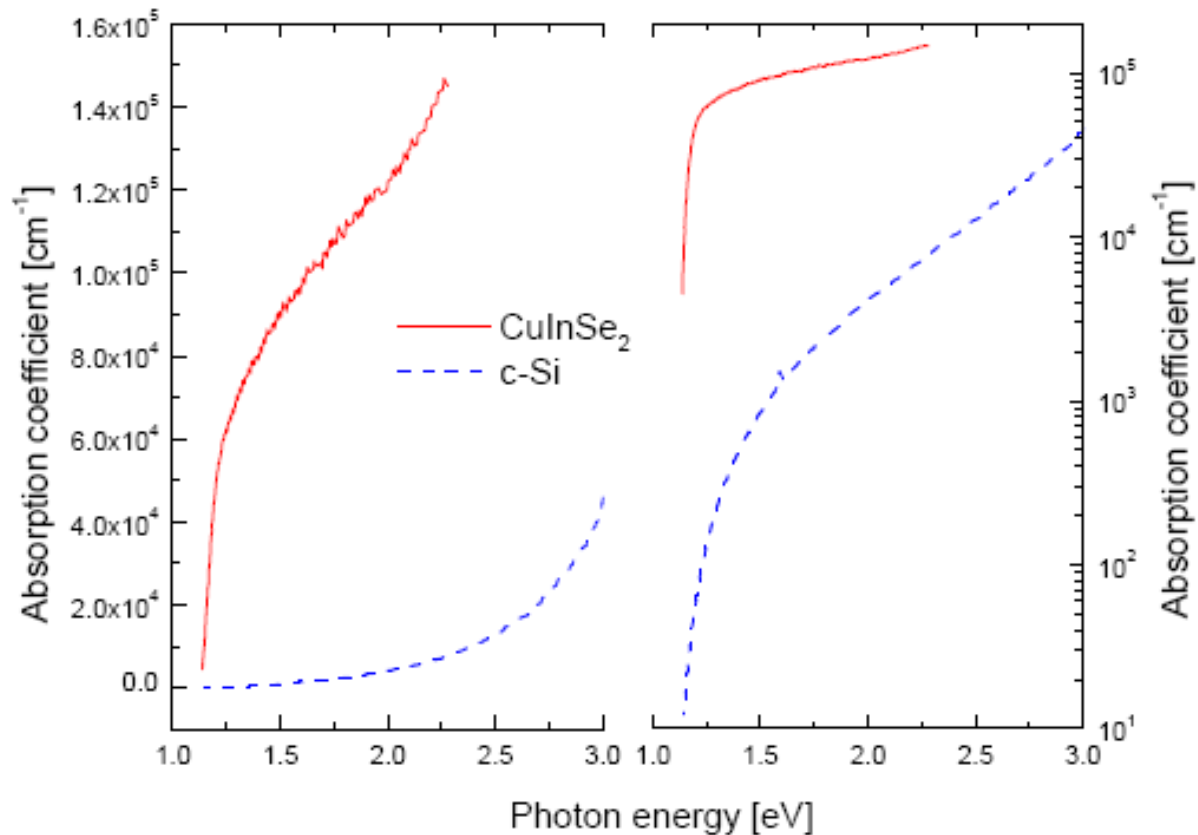
**CuInSe<sub>2</sub> 1 eV**



**Cu(In,Ga)Se<sub>2</sub> 1-1.7 eV**

**« CIGS »**

# Spectral absorption



Direct bandgap (CuInSe<sub>2</sub>)

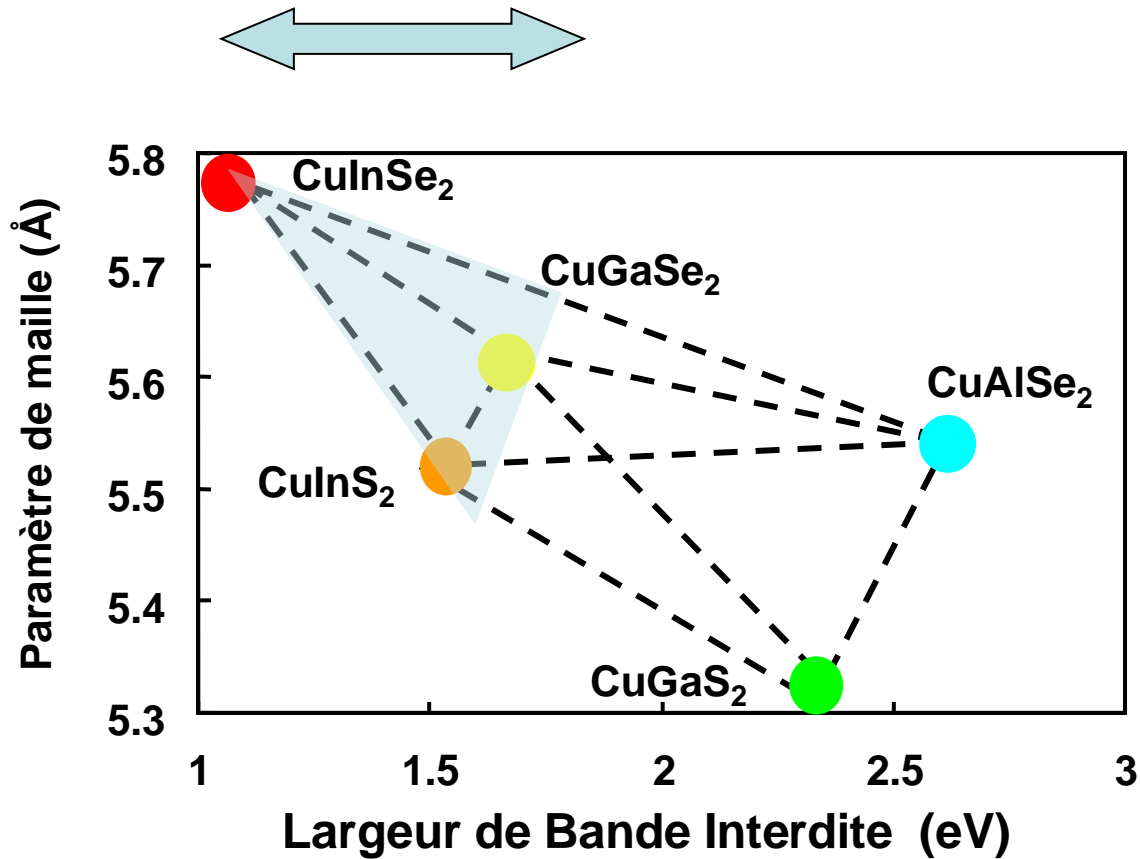
Indirect bandgap (Si)

(additional phonon required)

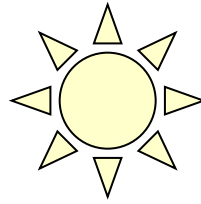
Solar Cells

© F.-J. Haug, ETH Zürich

# La famille CIS



Absorbeurs les plus efficaces:  $\text{Cu(In,Ga)Se}_2$   
et  $\text{CuIn(S,Se)}_2$



Contact

CdS, ZnS 50nm

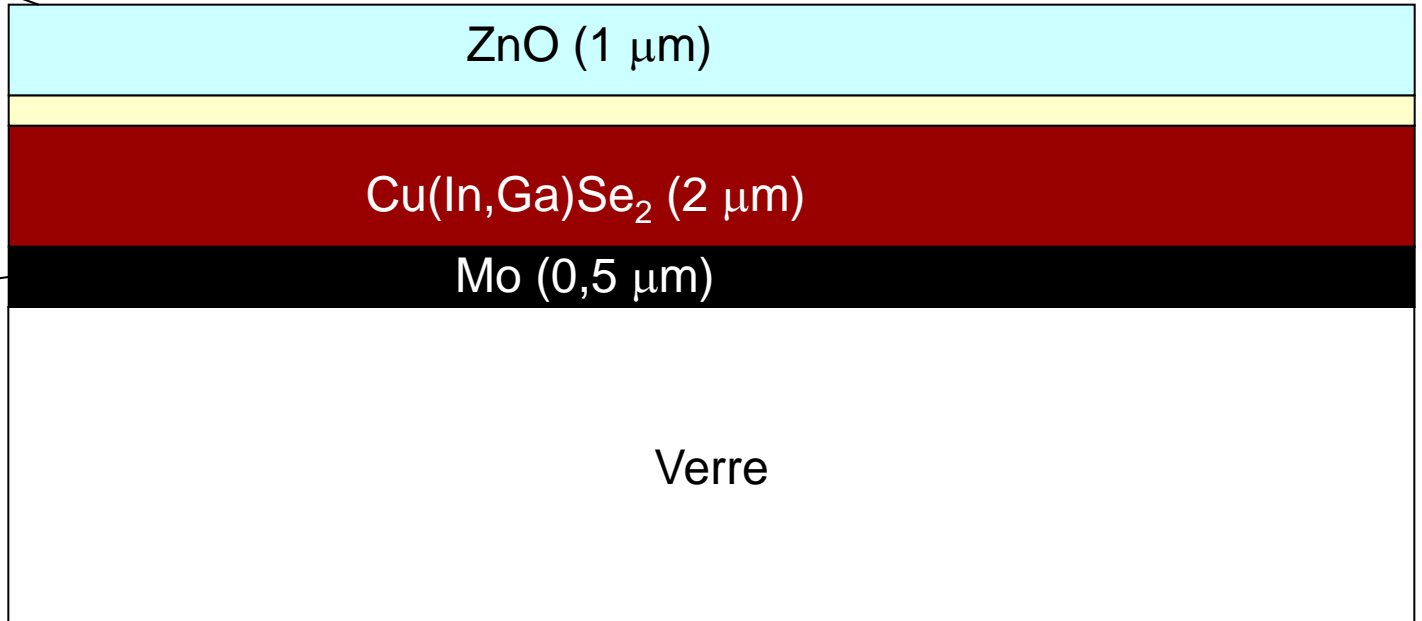
ZnO (1  $\mu\text{m}$ )

Cu(In,Ga)Se<sub>2</sub> (2  $\mu\text{m}$ )

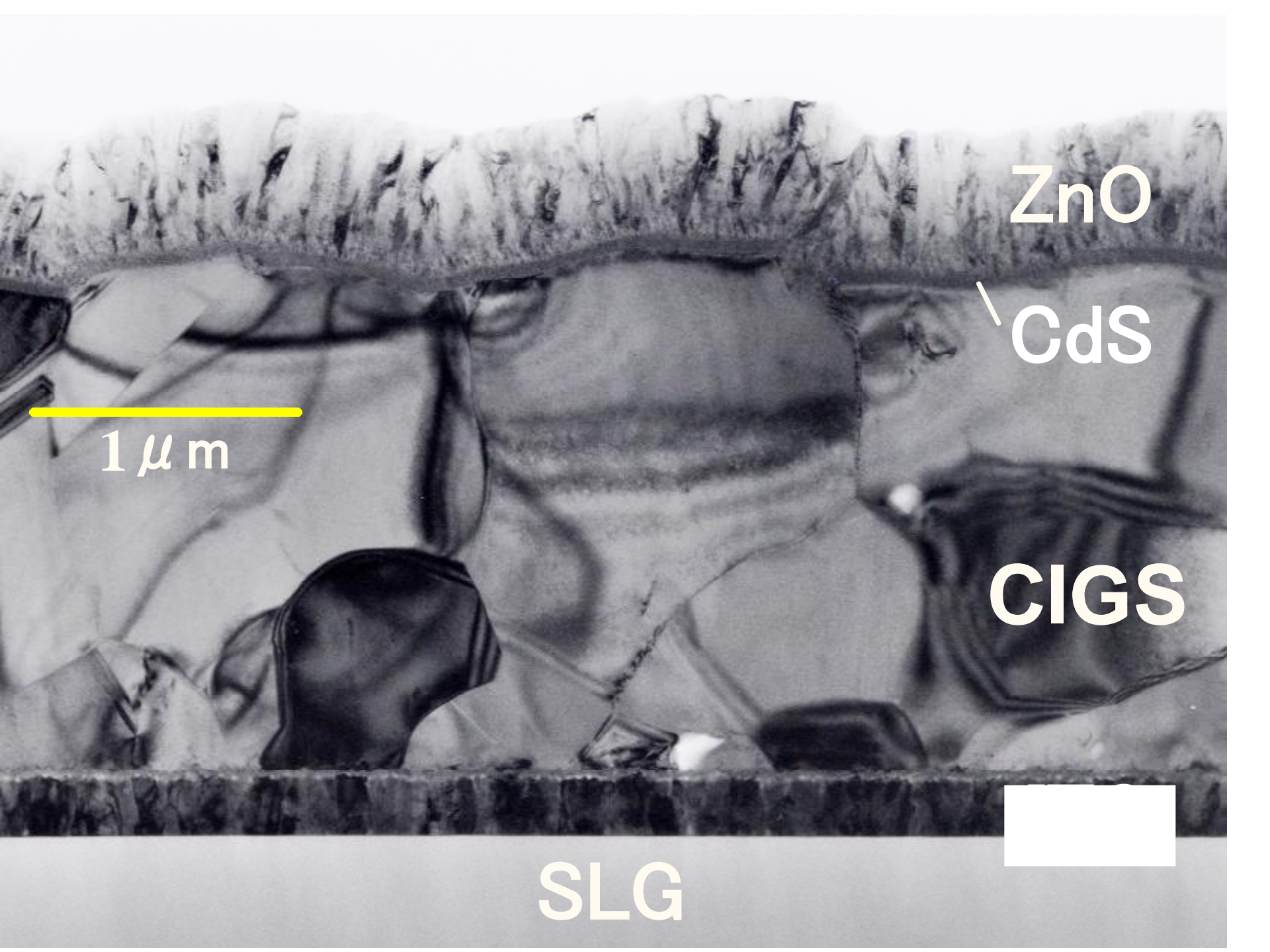
Mo (0,5  $\mu\text{m}$ )

Contact

Verre







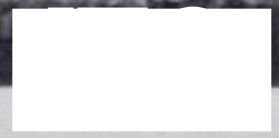
ZnO

CdS

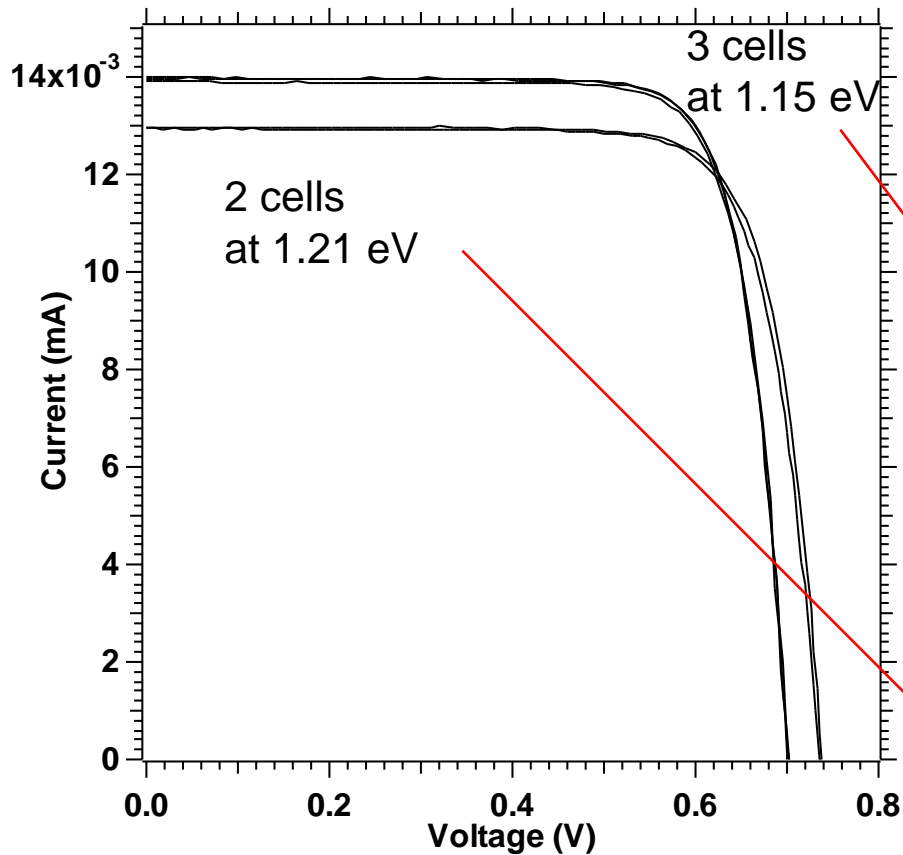
CIGS

SLG

1 μm



# Valeur record 2010 20 % !!



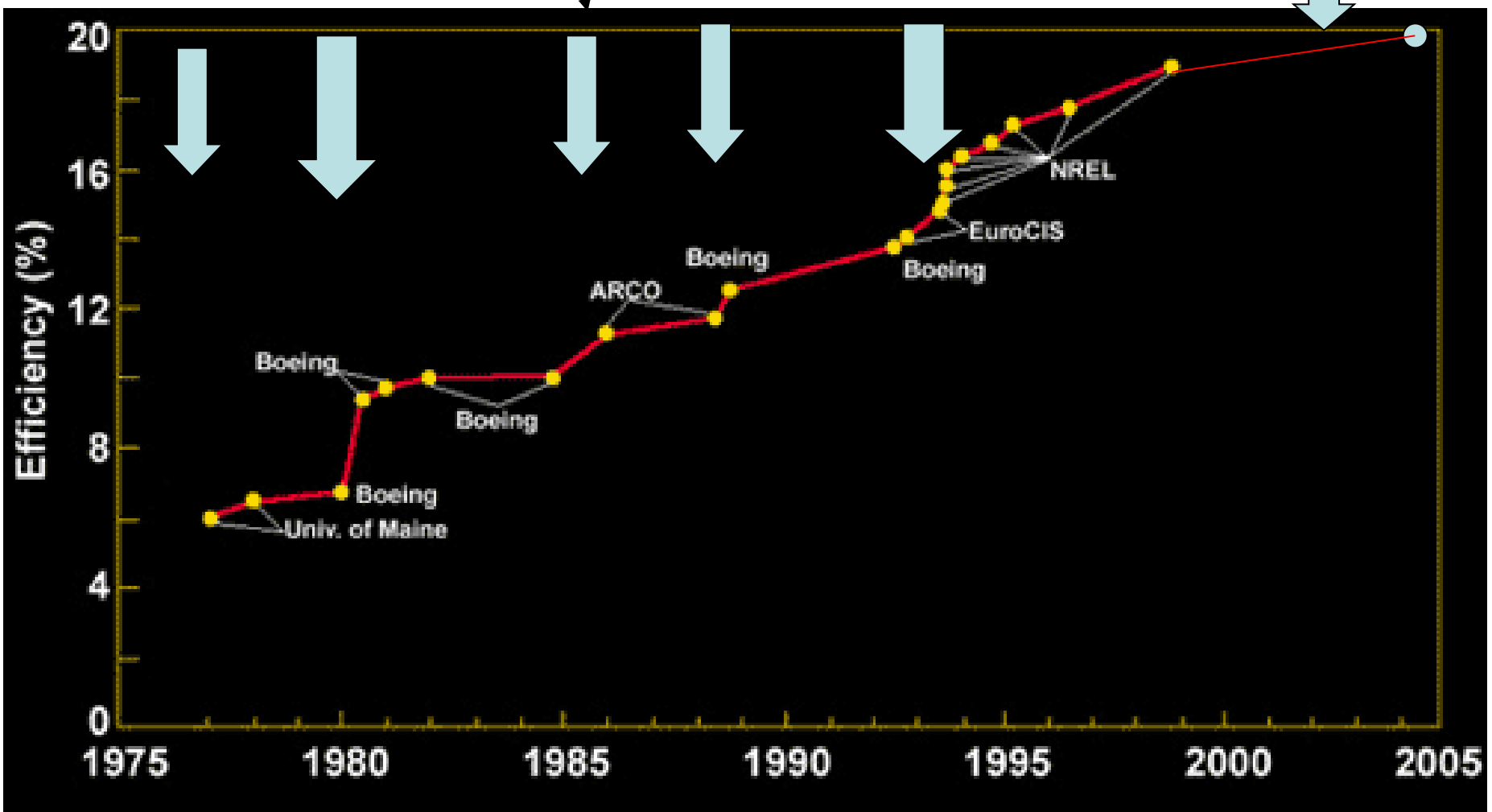
Sample Number	$V_{oc}$ (V)	$J_{sc}$ (mA/cm <sup>2</sup> )	Fill Factor (%)	Efficiency (%)
S2212-B1-3	0.701	34.60	79.65	19.3
S2212-B1-4	0.704	34.33	79.48	19.2
S2212-B1-5	0.703	34.08	79.23	19.0
S2213-A1-3	0.740	31.72	78.47	18.4
S2213-A1-4	0.737	31.66	78.08	18.2

Par courtoisie  
 Dr. K. Ramanathan  
 E MRS 2004

K. Ramanathan et al. Thin Solid Films 480(2005)499



# Ruptures

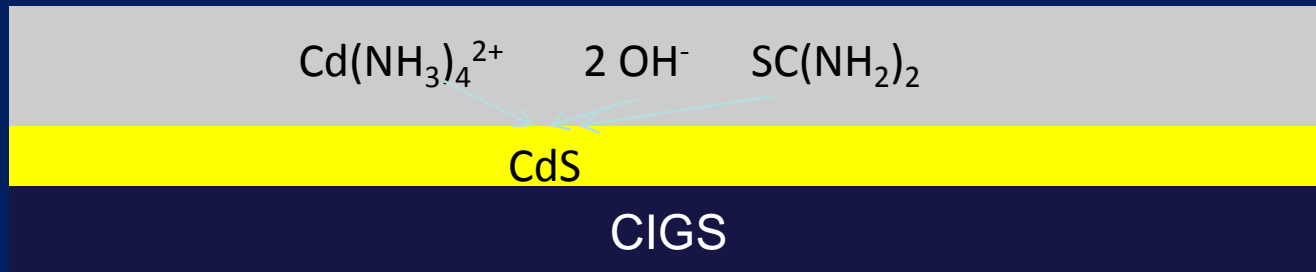


# Chemical bath Deposition

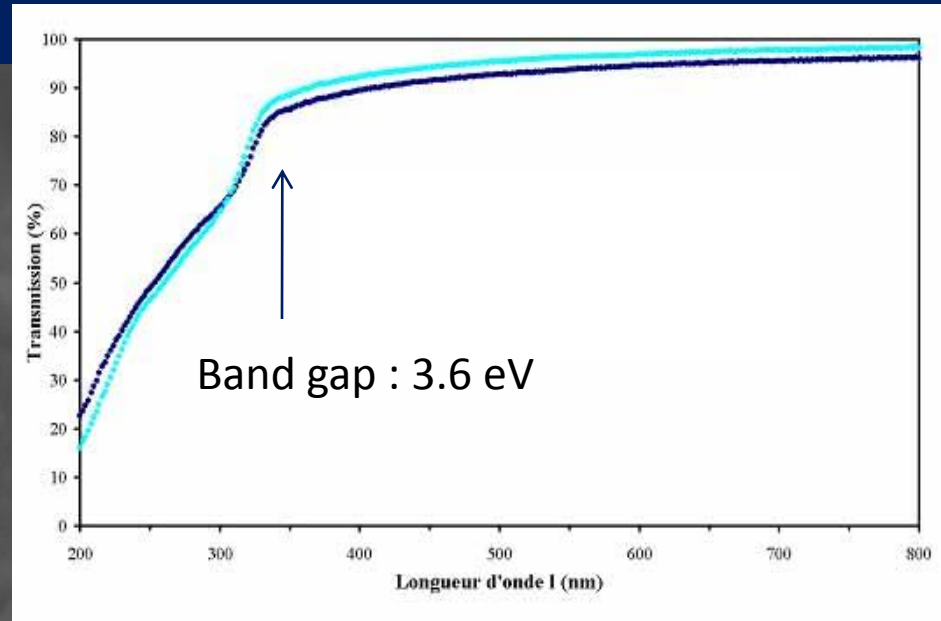
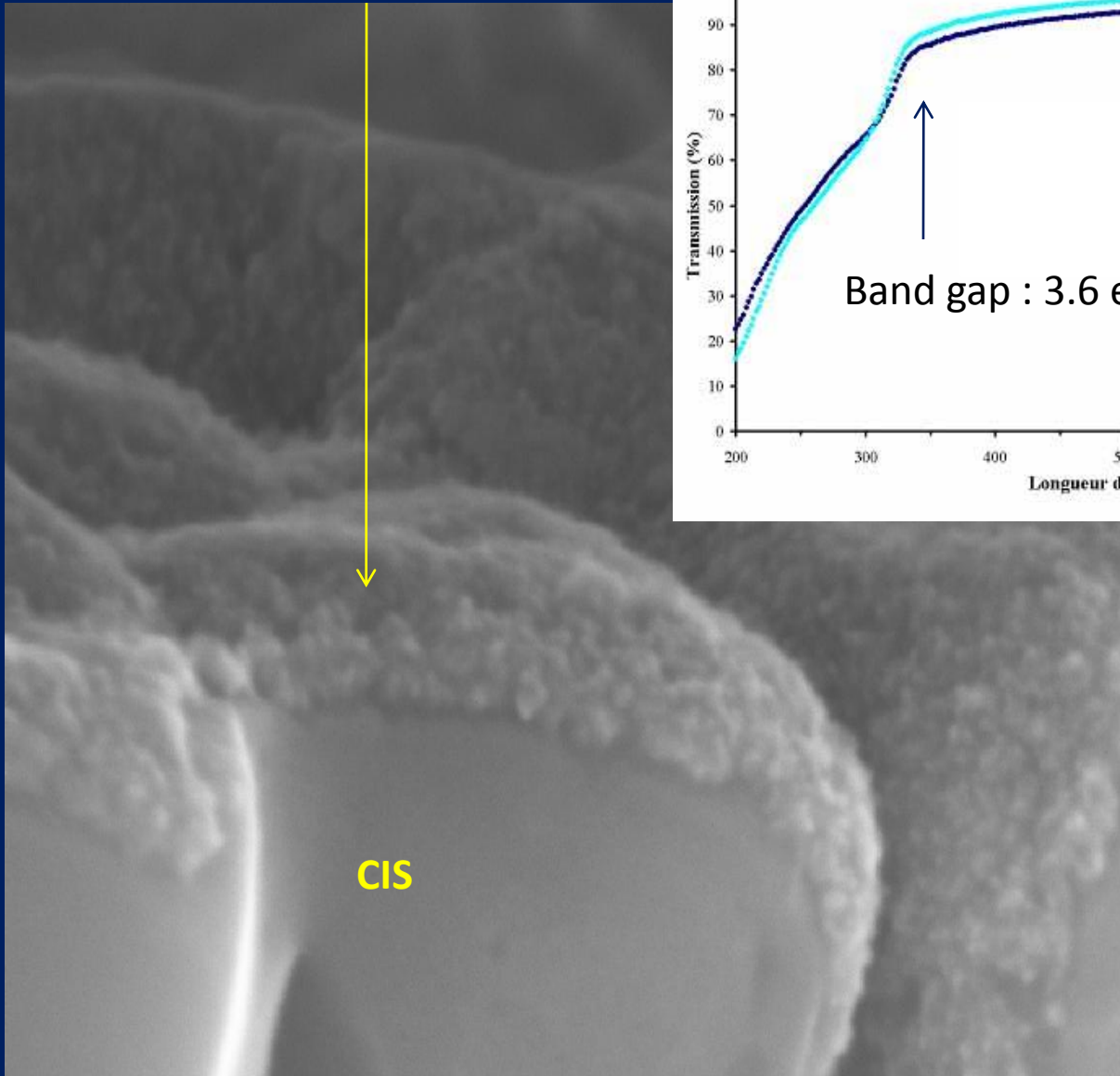
Analogous to CVD



In aqueous solution, 60-80°C, surface controlled  
Conformal growth, Full coverage for 30-40 nm



ZnS Buffer



Covering  
Nanocrystalline  
Transparency

100nm\*

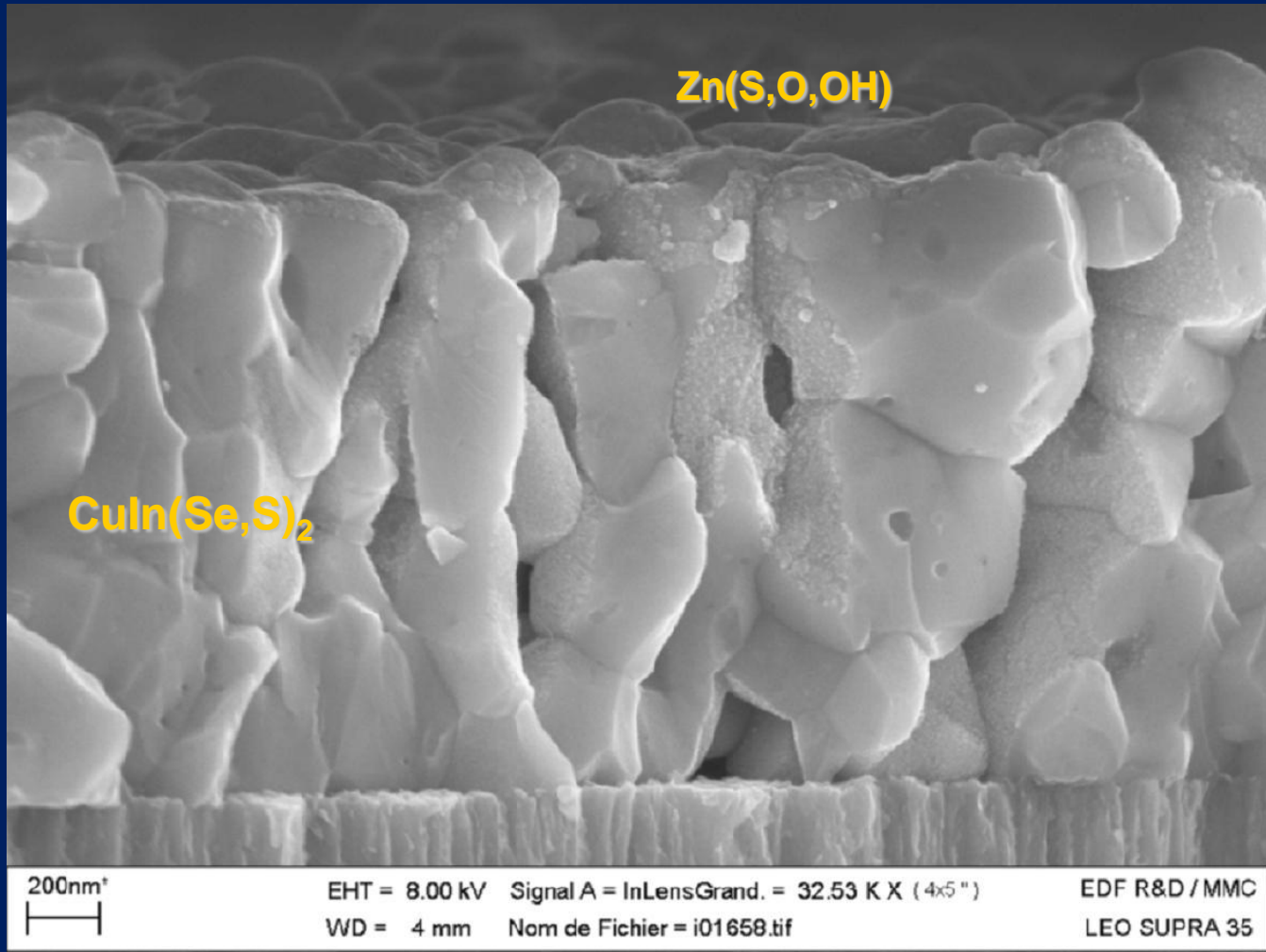


EHT = 8.00 kV Signal A = InLensGrand. = 177.12 K X (4x5")

WD = 4 mm Norm de Fichier = i01656.tif

EDF R&D / MMC

LEO SUPRA 35



$Zn(S,O,OH)$

$CuIn(Se,S)_2$

200nm  
|-----|

EHT = 8.00 kV Signal A = InLensGrand. = 32.53 K X (4x5 ")  
WD = 4 mm Nom de Fichier = i01658.tif

EDF R&D / MMC  
LEO SUPRA 35

XXV.—*On the Synthesis of Galena by Means of Thiocarbamide, and the Deposition of Lead Sulphide as a Specular Film.*

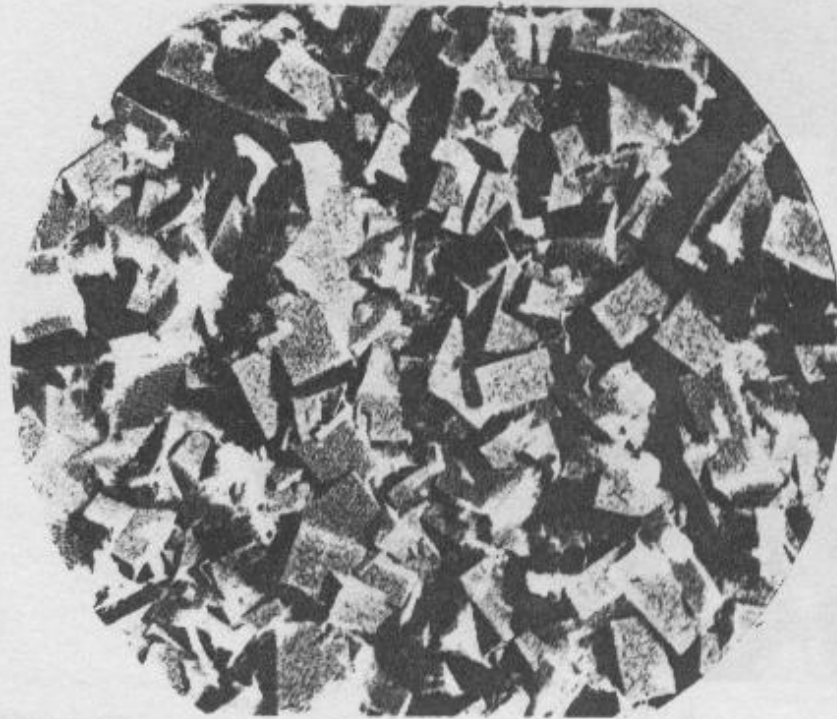
By J. EMERSON-REYNOLDS, M.D., F.R.S.

THIOCARBAMIDE, or sulphur urea, is now well known to be easily desulphurated by certain metallic oxides and hydrates, notably those of silver, mercury, and lead. The products, on treatment with a simple oxide, are metallic sulphide, water, and cyanamide—



When free alkali is present the cyanamide soon changes into the polymer, dicyanodiamide. In using the hydrate of lead shortly after the discovery of thiocarbamide, it was observed that when the latter was heated with an alkaline solution of lead hydrate, the metallic sulphide sometimes separated in a galenoid form, and became firmly attached as a specular layer to the sides of the vessel.

When once thiocarbamide can be produced at a sufficiently cheap rate, galena plating may be applied to many useful purposes; but the existing patent rights controlling the production of ammonium thiocyanate, from which thiocarbamide is produced, prevent at present the use of the latter in quantity.



—| 1 μ

Abb. 1. Übermikroskopaufnahme einer Bleisulfidschicht bei Verwendung konzentrierter Lösungen.  
Vergrößerung 7000fach (Goldabdruck).

Dépôt chimique de PbS



# La chimie dans les méthodes d'élaboration



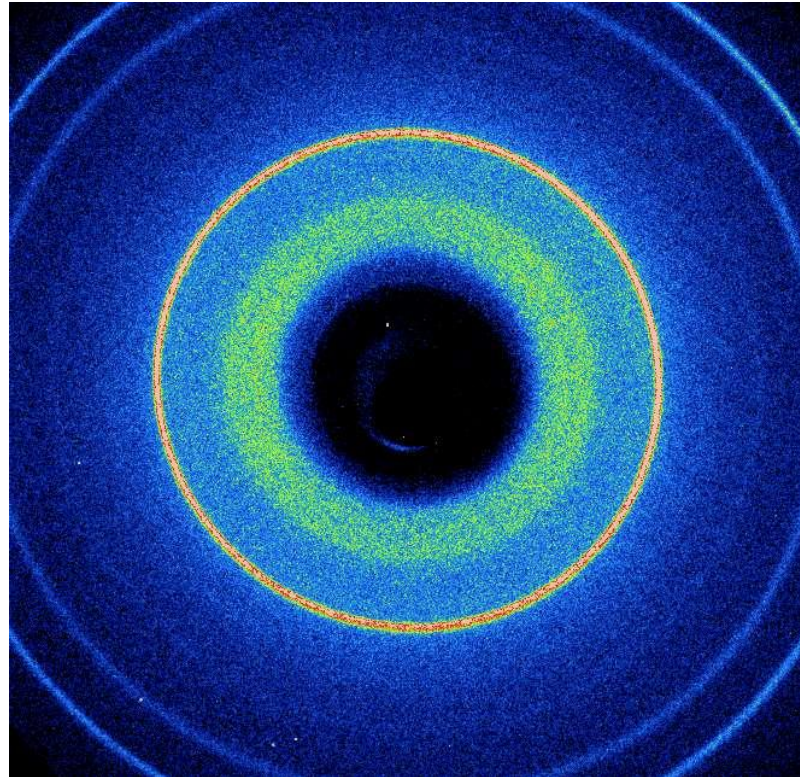
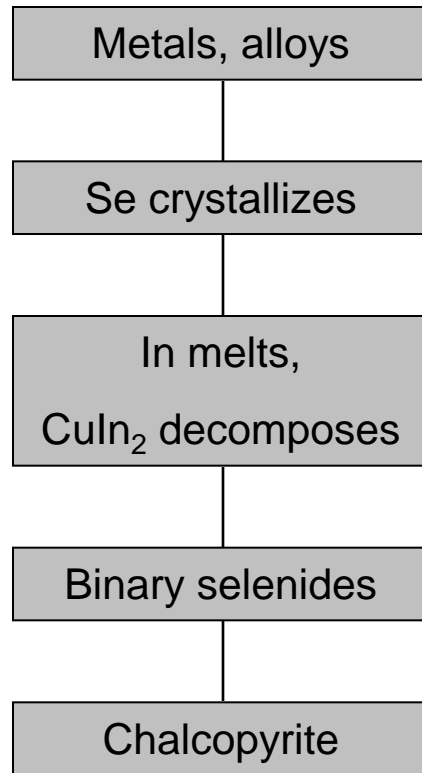
Contenu « chimie »

- Méthodes atmosphériques
  - sérigraphie
  - Electrodepôt
  - Bas coûts
- Méthodes séquentielles sous vide
  - (pulvérisation cathodique + recuit thermique)
- Coévaporation sous ultravide
  - Rendements records + coûts élevés

# Sequential methods (sputtering + annealing)

## Polycrystalline Phases during the formation of $\text{Cu}(\text{In},\text{Al})\text{Se}_2$

S. Jost et al, Phys. Status Solidi a, 203(2006)2581



S. Jost<sup>1</sup>, F. Hergert<sup>1</sup>, R. Hock<sup>1</sup>, M. Purwins<sup>2</sup>, R. Enderle<sup>2</sup>

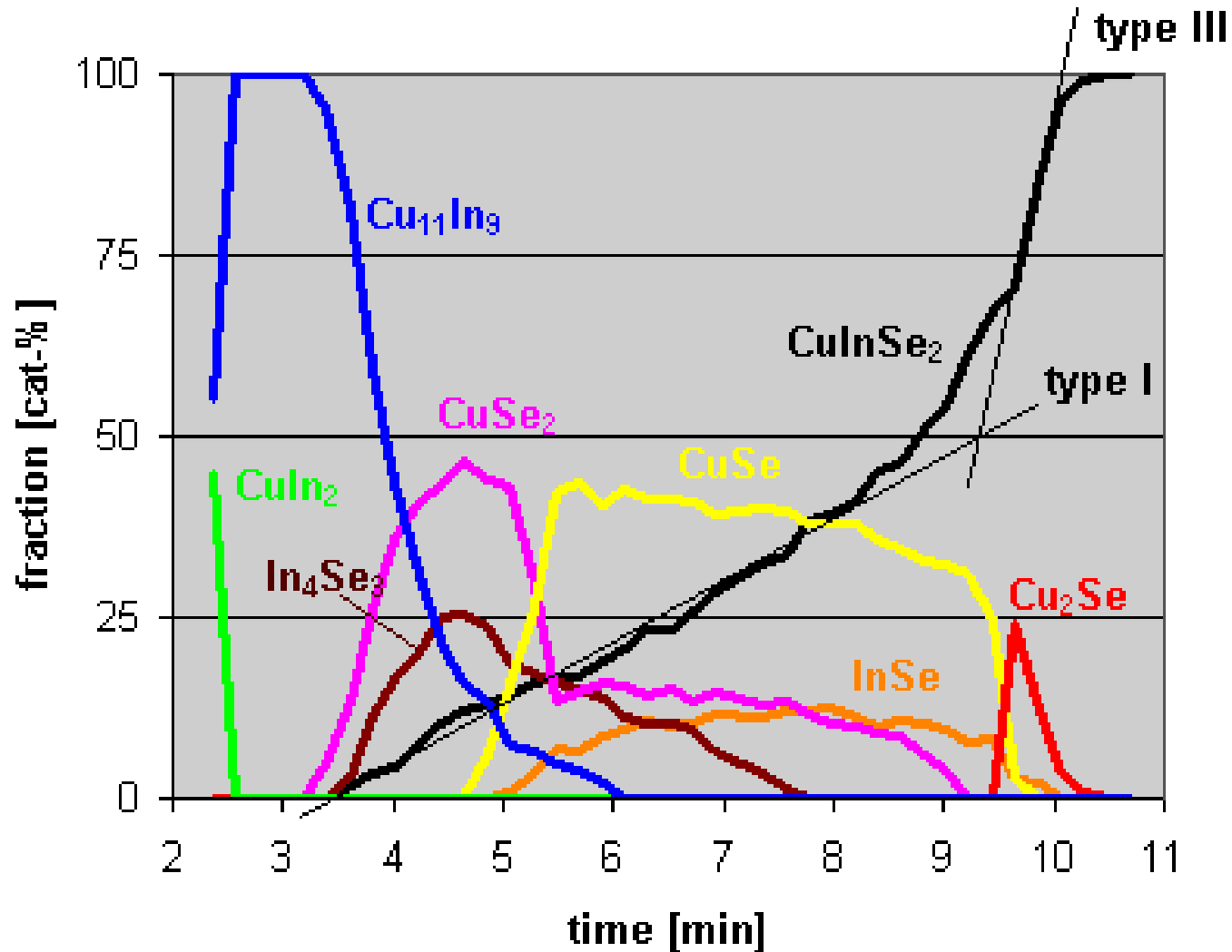
<sup>1</sup> Chair for Crystallography and Structural Physics, University of Erlangen

<sup>2</sup> Crystal Growth Laboratory, Department of Materials Science VI, University of Erlangen

# Formation of $\text{CuInSe}_2$ by reactive Thermal annealing of Cu-In precursors

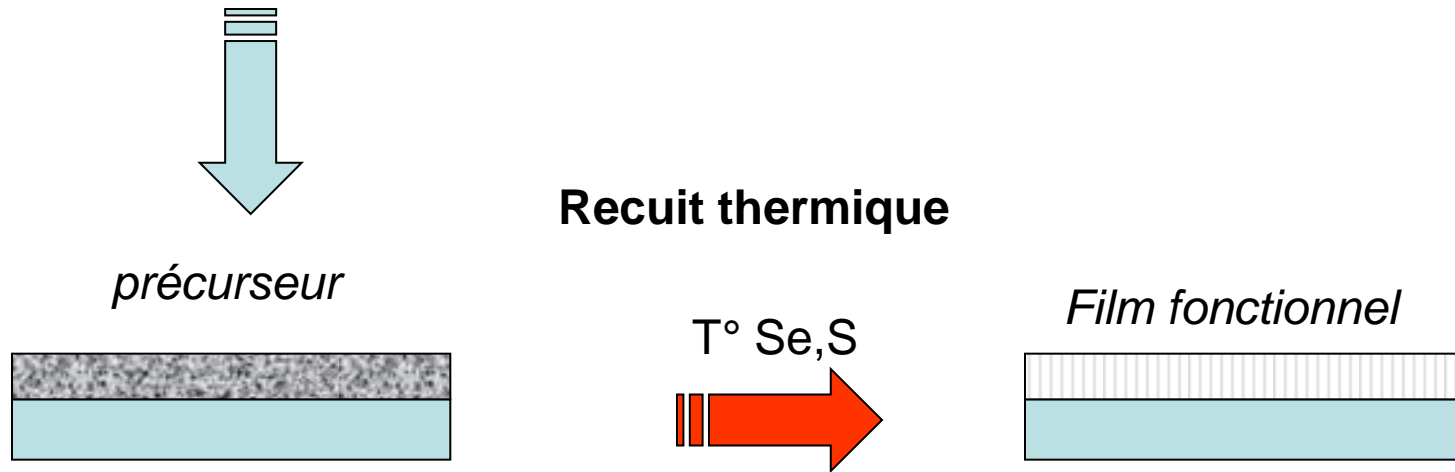
F. Hergert et al.: ICTMC 14  
J. Phys. Chem. Sol. 67 2005 1903

S. Jost et al. ICTMC15



# Méthodes atmosphériques

- Sérigraphie
- Electrodepôt



# Exemple de sérigraphie (ISET)

V. Kapur et al.  
Mat. Res. Symp. Proc.  
Vol. 668(2001)

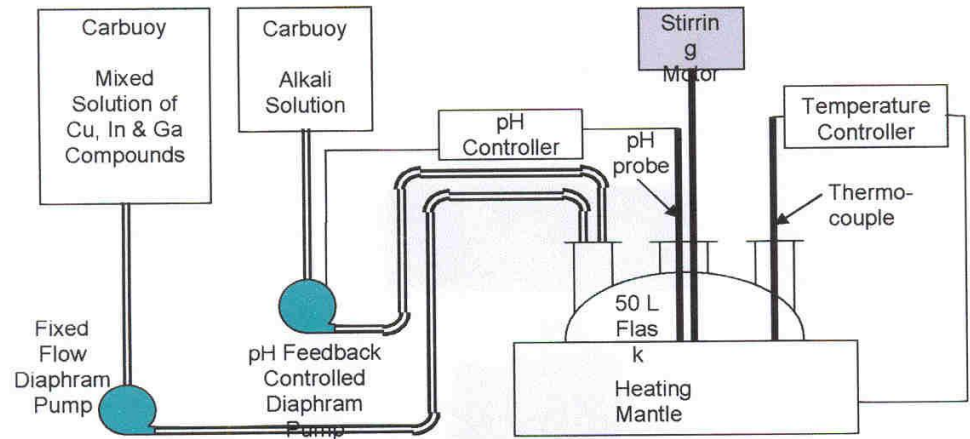
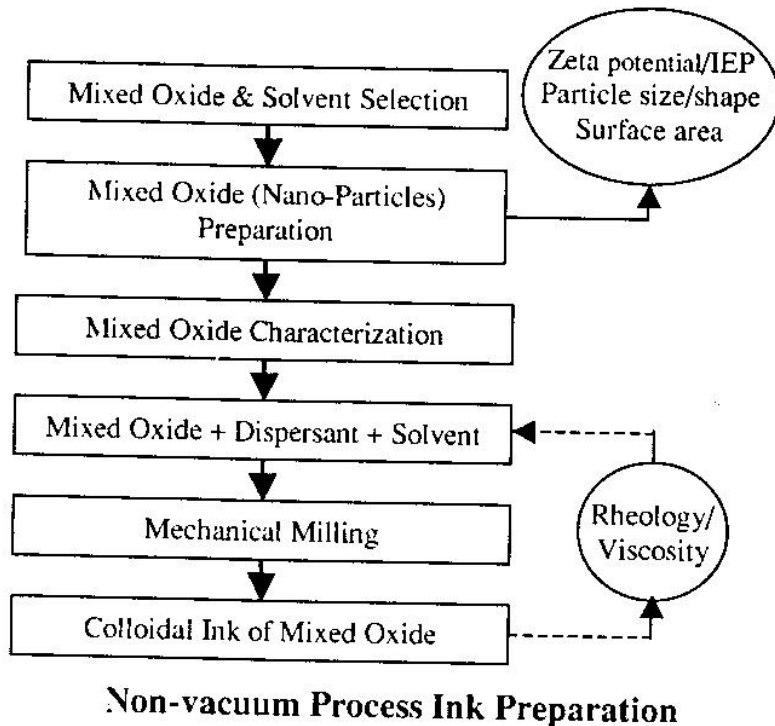
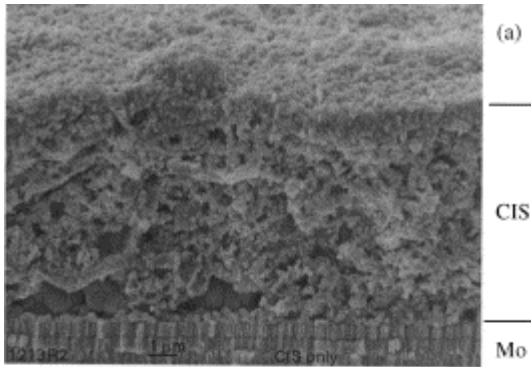


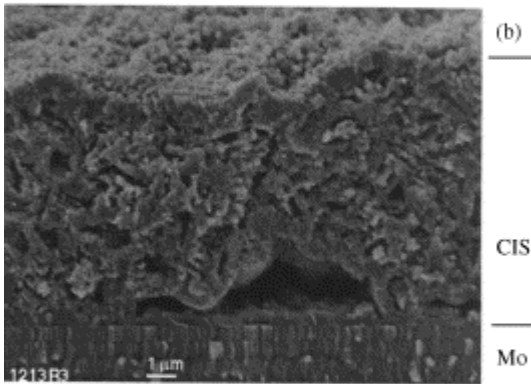
Figure 4. Co-precipitation setup for preparing inks.

# Précurseur nanocristallin sélénisé (technologie ISET)

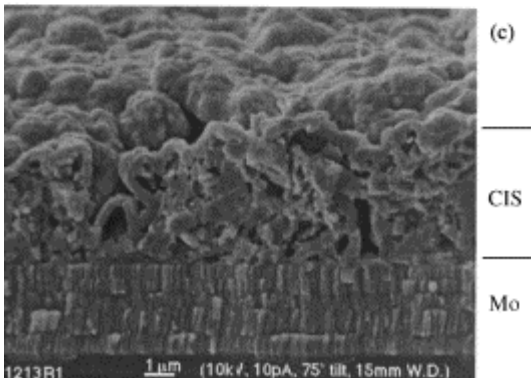
G. Norsworthy at al. Solar Energy Materials 60(2000)127



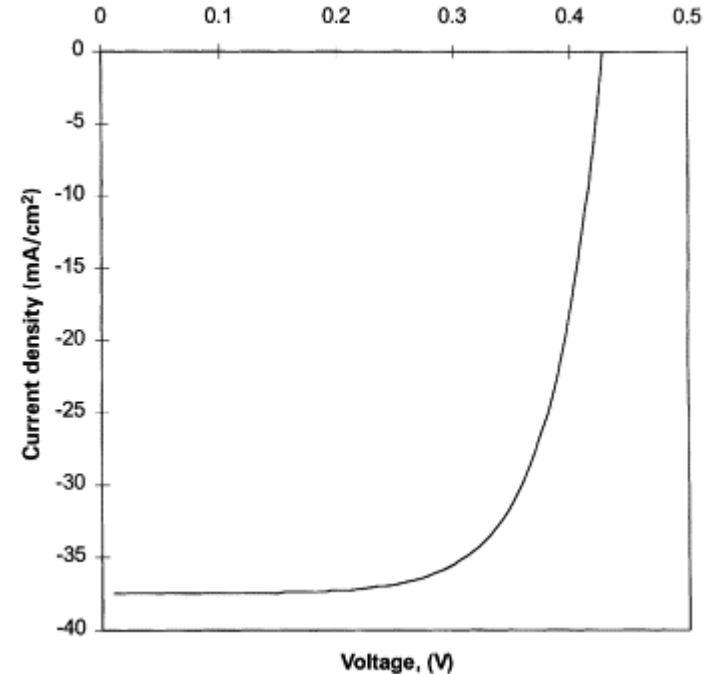
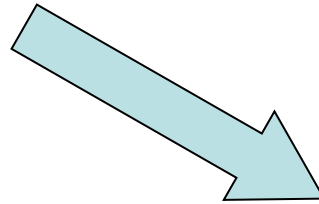
(a)  $\text{Cu/In}=0.88$



(b)  $\text{Cu/In}=0.98$



(c)  $\text{Cu/In}=1.05$ .

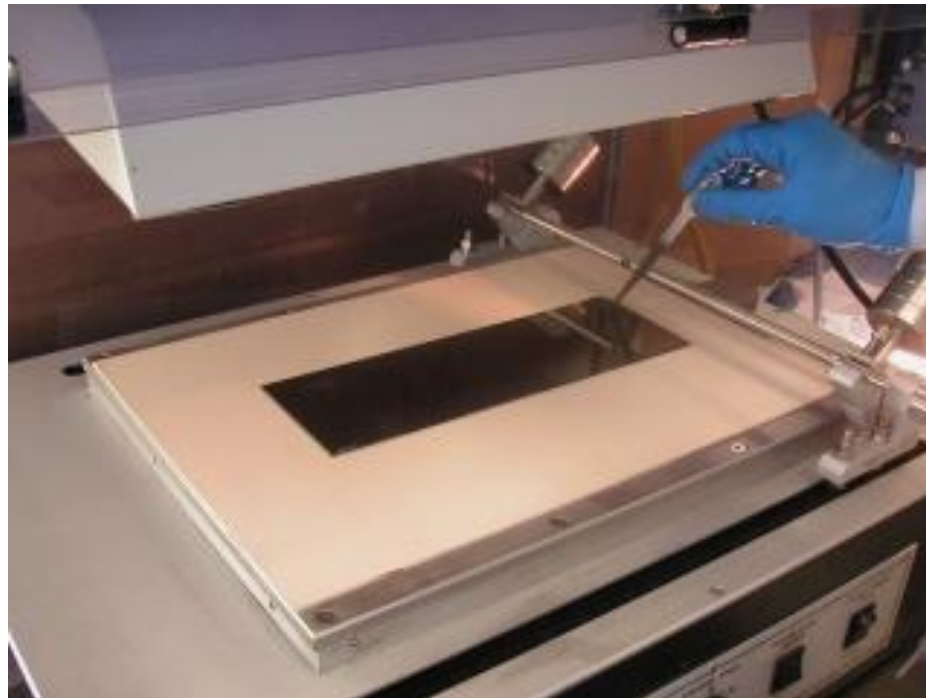


Area=0.1 cm<sup>2</sup>,  $\eta=10.56\%$ ,  $V_{oc}=0.43$  V,  $J_{sc}=37.5$  mA/cm<sup>2</sup> and FF=65.5%.

## Research & Development

ISET's team of scientists and engineers have obtained the following results for CIGS solar cells  
**CIS-based Non-Vacuum Processing**

<b>Substrate</b>	<b>Efficiency</b>	<b>Air Mass Index</b>
Soda Lime Glass	13.6%	AM1.5 <sup>a</sup>
Molybdenum Foil	13.0%	AM1.5
Titanium Foil	9.5%	AM1.5
Polyimide Film	9.3%	AM0 <sup>b</sup>



L'électrodépôt :

Une référence : L'industrie des revêtement électrochimique



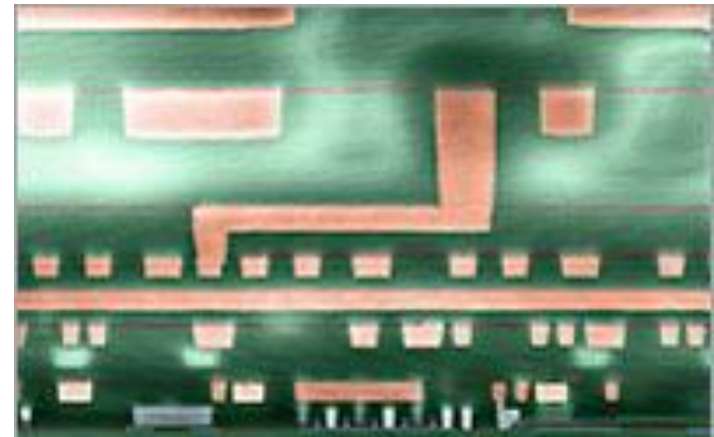
1.7 10<sup>6</sup> tons/year  
1 Billion m<sup>2</sup>/year



100 GWc /year  
Equivalent PV production



**Another example : From the electrolytic preparation of ultrapure copper (Codelco, Chile July 2006)**



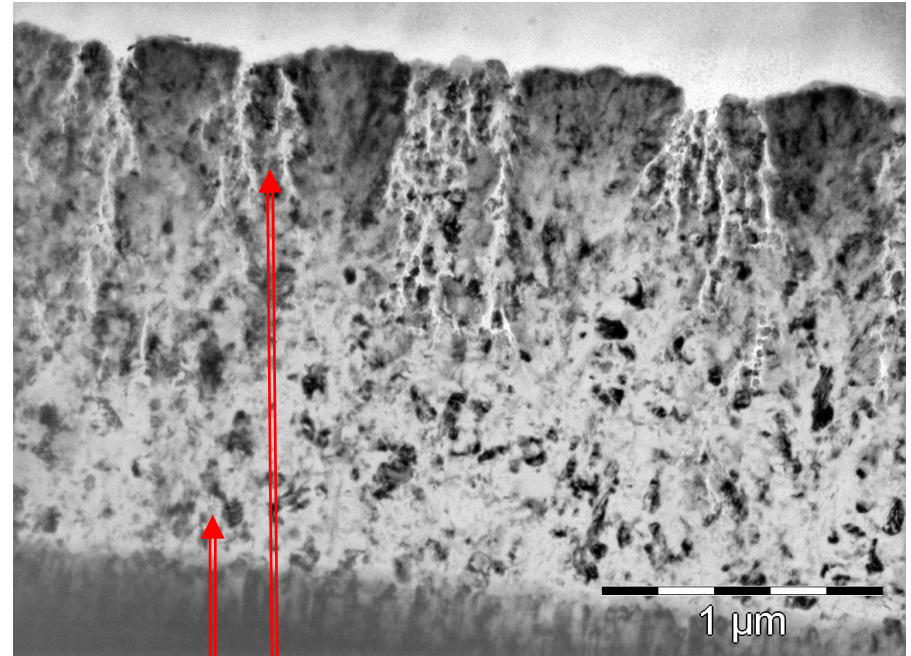
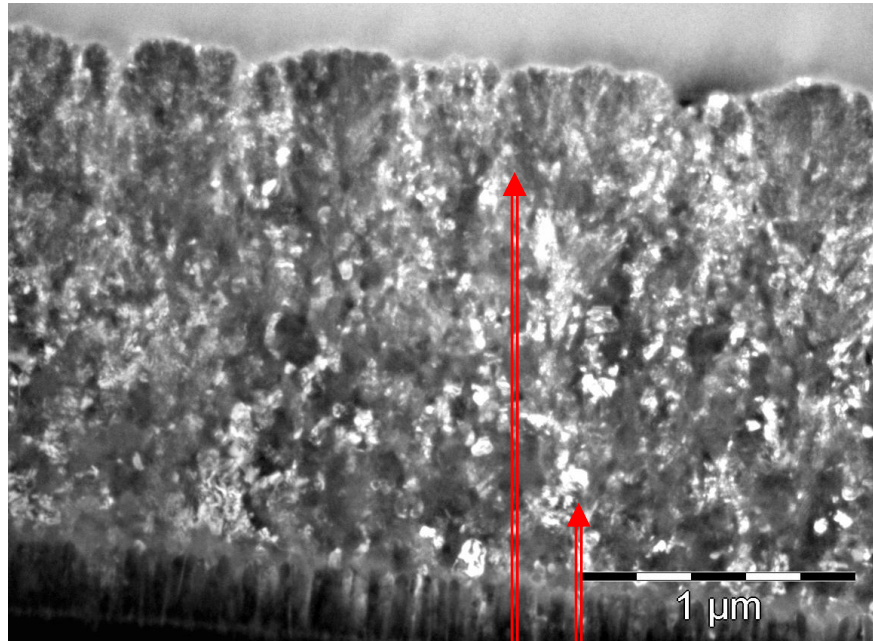
10  
levels

4 microns

**Down to the Damasene Process IBM**



# Microscopie électronique à transmission



Champ sombre

Champ clair

Taille moyenne des grains :

arrière 50 nm

avant 20 nm

Présence de crevasses

signature XRD :

$\text{CuInSe}_2$  et  $\text{Cu}_2\text{Se}$

J. Kessler et al., Barcelona 05

# Traitement de recuit rapide

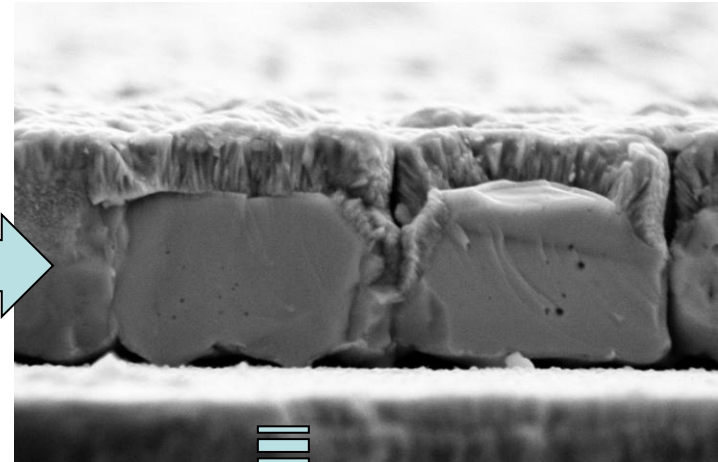
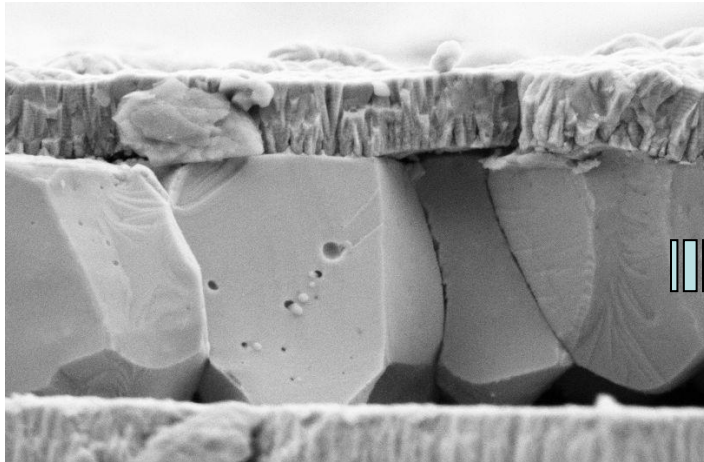
IRDEP., Barcelone 2005

0% S

$\text{CuInSe}_2$  1 eV

≈ 40% S

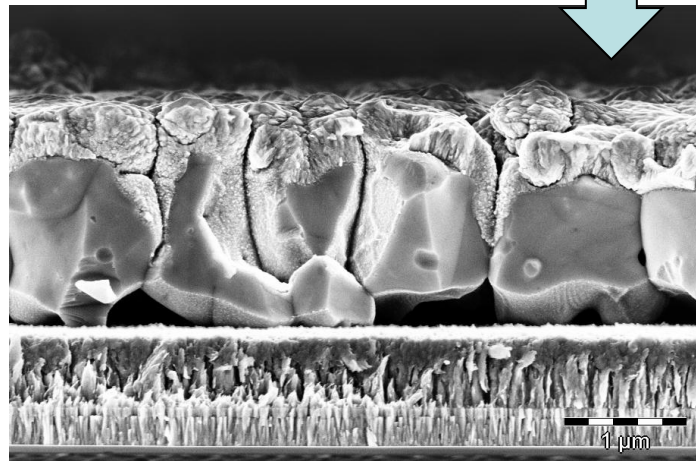
$\text{CuInSe}_{0.6}\text{S}_{0.4}$  1,2 eV



90-95 % S

$\text{CuInSe}_{0.05}\text{S}_{0.95}$  1,45 eV

**11,4% record cellule**  
**7-8% upscale**



# Tolérance chimique exceptionnelle

- Tolerance to defects (grain boundaries, surfaces) Tolérance aux « défauts » structuraux: joints de grains
- Tolerance to large deviations from stoichiometry (up to a few %)
- Tolerance to impurities
- Self doping by stoichiometric deviations
- Good optoelectronic properties
- **Self-repair properties** (copper ionic mobility)

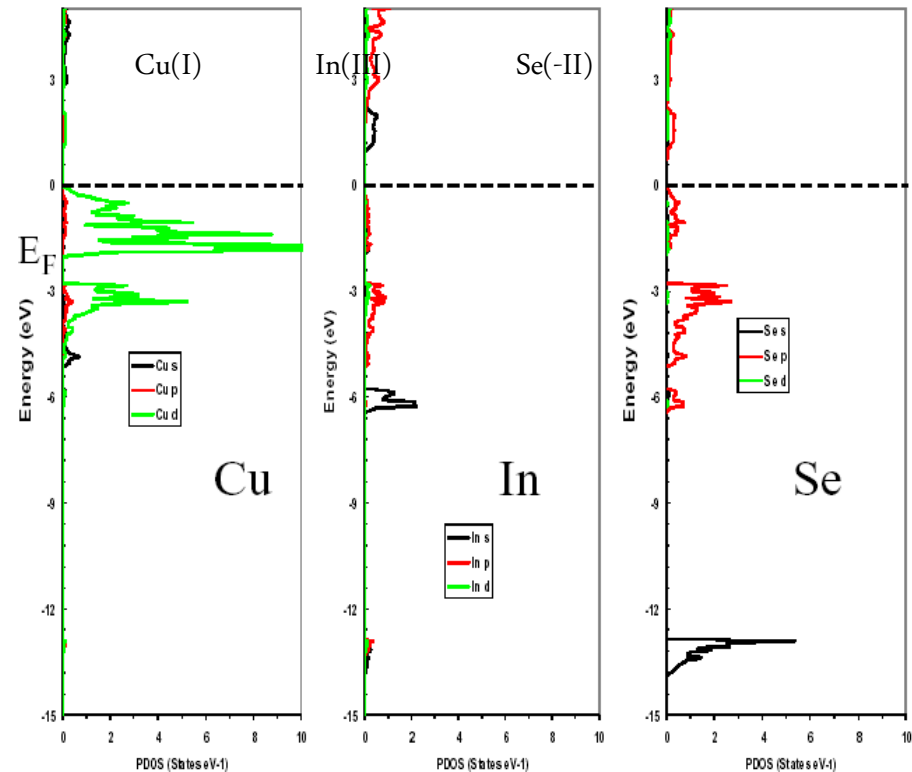
## Challenges

**in solid state chemistry, materials chemistry,  
correlations between chemistry and electronic properties**

*Exemple of puzzling effect : why much more tolerant than Si and III-V's*

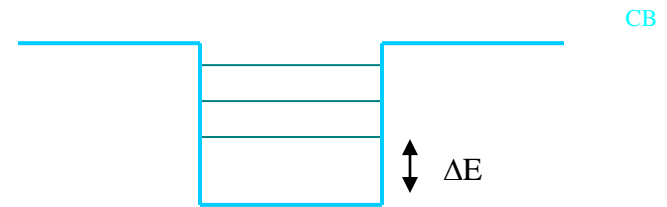
# Calculs ab initio

- Cu-(S,Se) Anti bonding VB
  - easy formation of (neutral) Cu related defects
- In-Se covalent Skeleton
  - Compound stability
- Neighbor phases structurally related, small gap,
  - Defects as "Q-dots", electrically inactive



Self-stabilisation properties

$$N_a, N_d \Leftrightarrow E_f \Leftrightarrow \Delta G_f \Leftrightarrow N_a, N_d$$

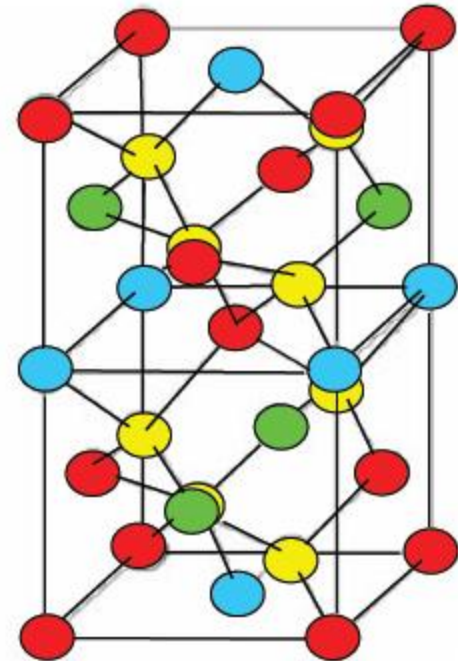
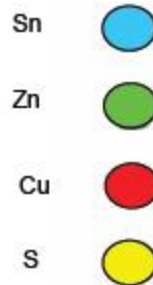
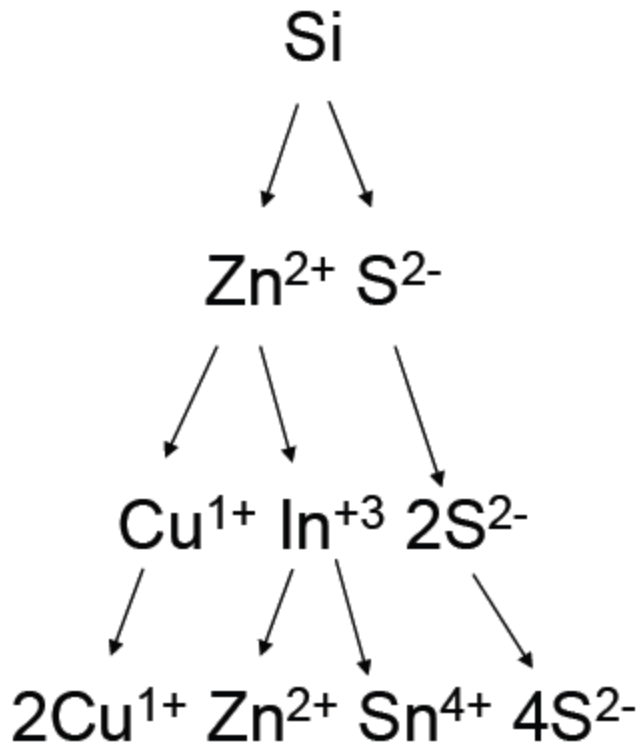


Source J.F. Guillemoles

## Durabilité : la question de l'Indium

Une voie de recherche : substituer l'indium par zinc + étain

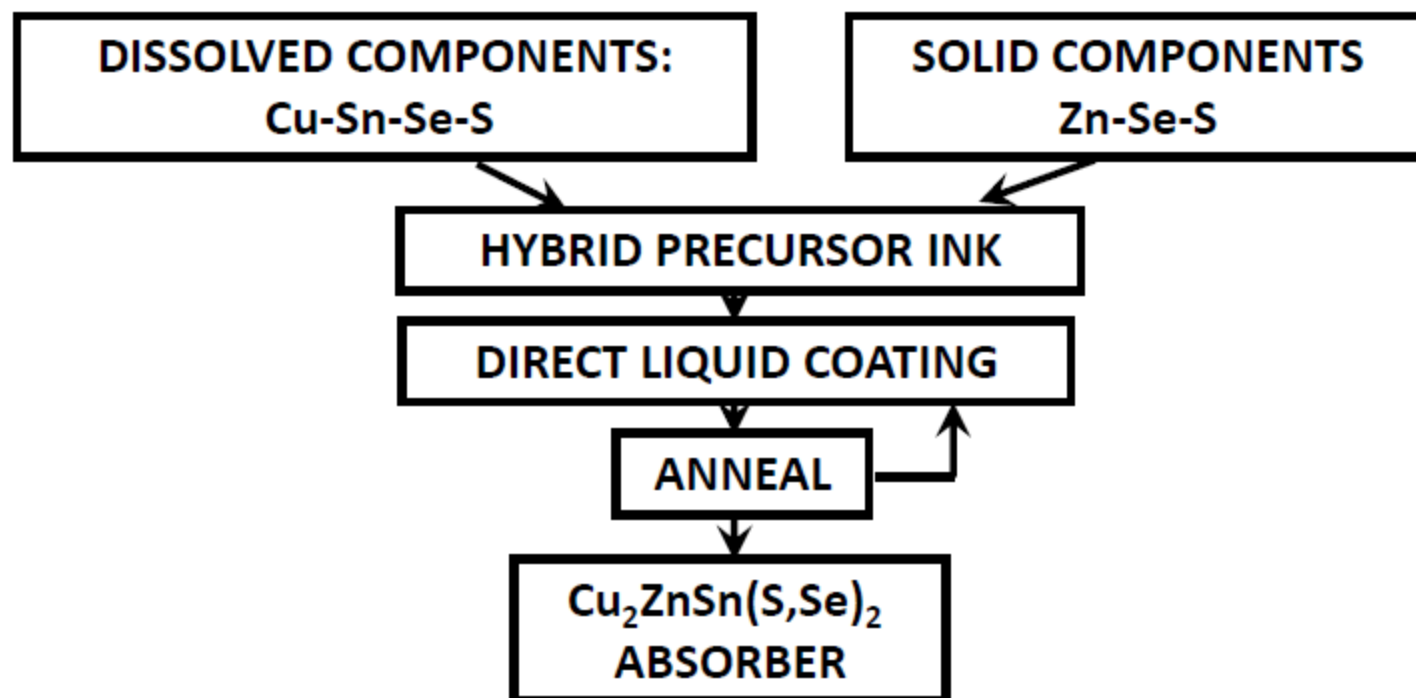
La piste Kesterite :  $\text{Cu}_2\text{ZnSn}(\text{S},\text{Se})_4$  1-1.7 eV



# High-Efficiency Solar Cell with Earth-Abundant Liquid-Processed Absorber

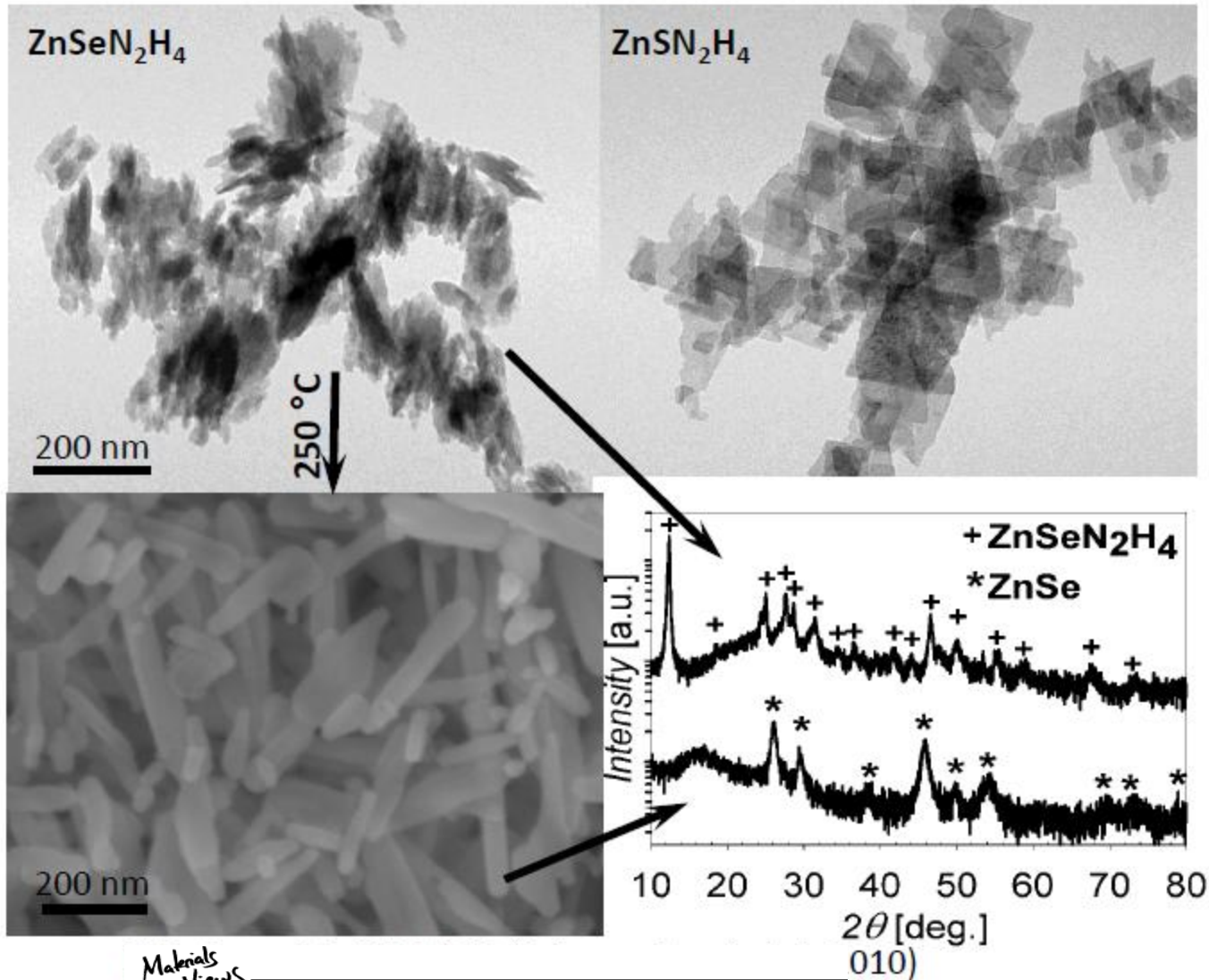
By Teodor K. Todorov, Kathleen B. Reuter, and David B. Mitzi\*

## Non-vacuum hybrid coating method





# Solid Zn chalcogenide hydrazinates



Materials  
Views

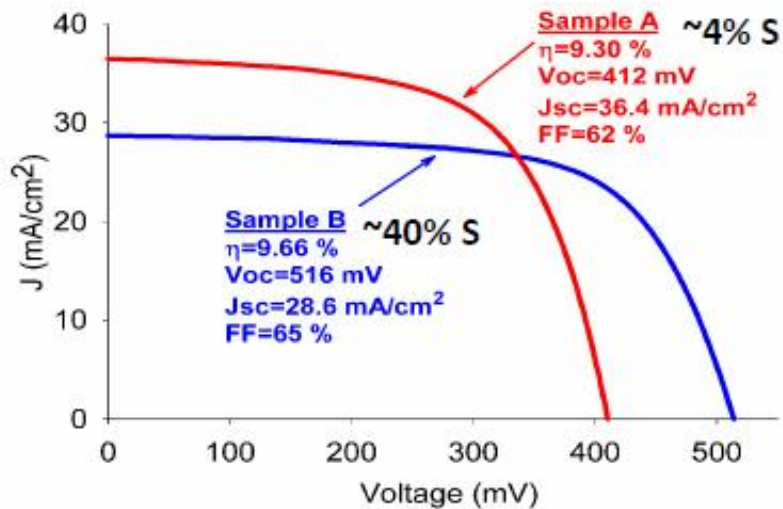
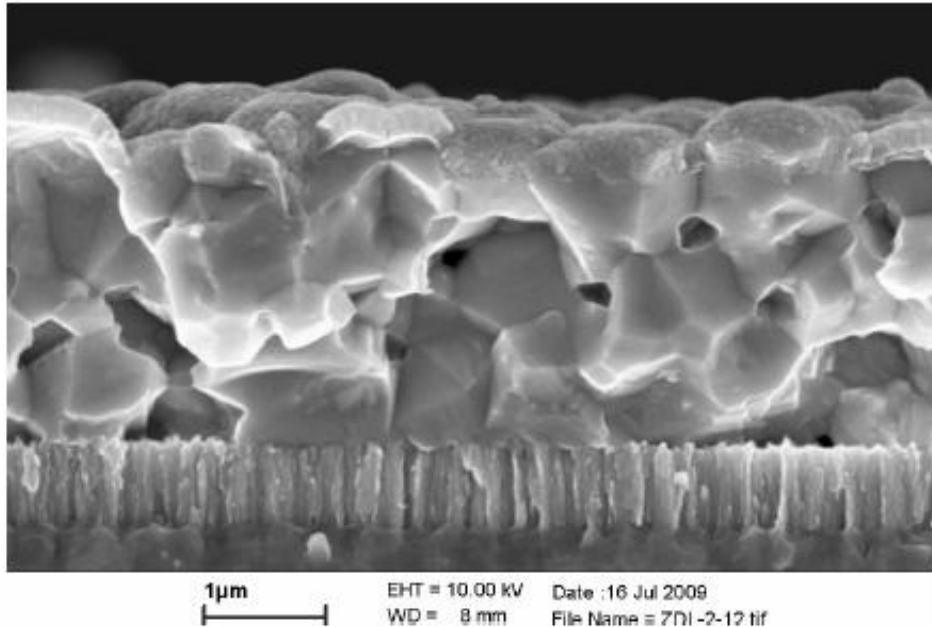
[www.MaterialsViews.com](http://www.MaterialsViews.com)

*Adv. Mater.* 2010, 22, 1–4

**High-Efficiency Solar Cell with Earth-Abundant  
Liquid-Processed Absorber**

By Teodor K. Todorov, Kathleen B. Reuter, and David B. Mitzi\*

# $\text{Cu}_2\text{ZnSn}(\text{S},\text{Se})_4$ device



Materials  
Views

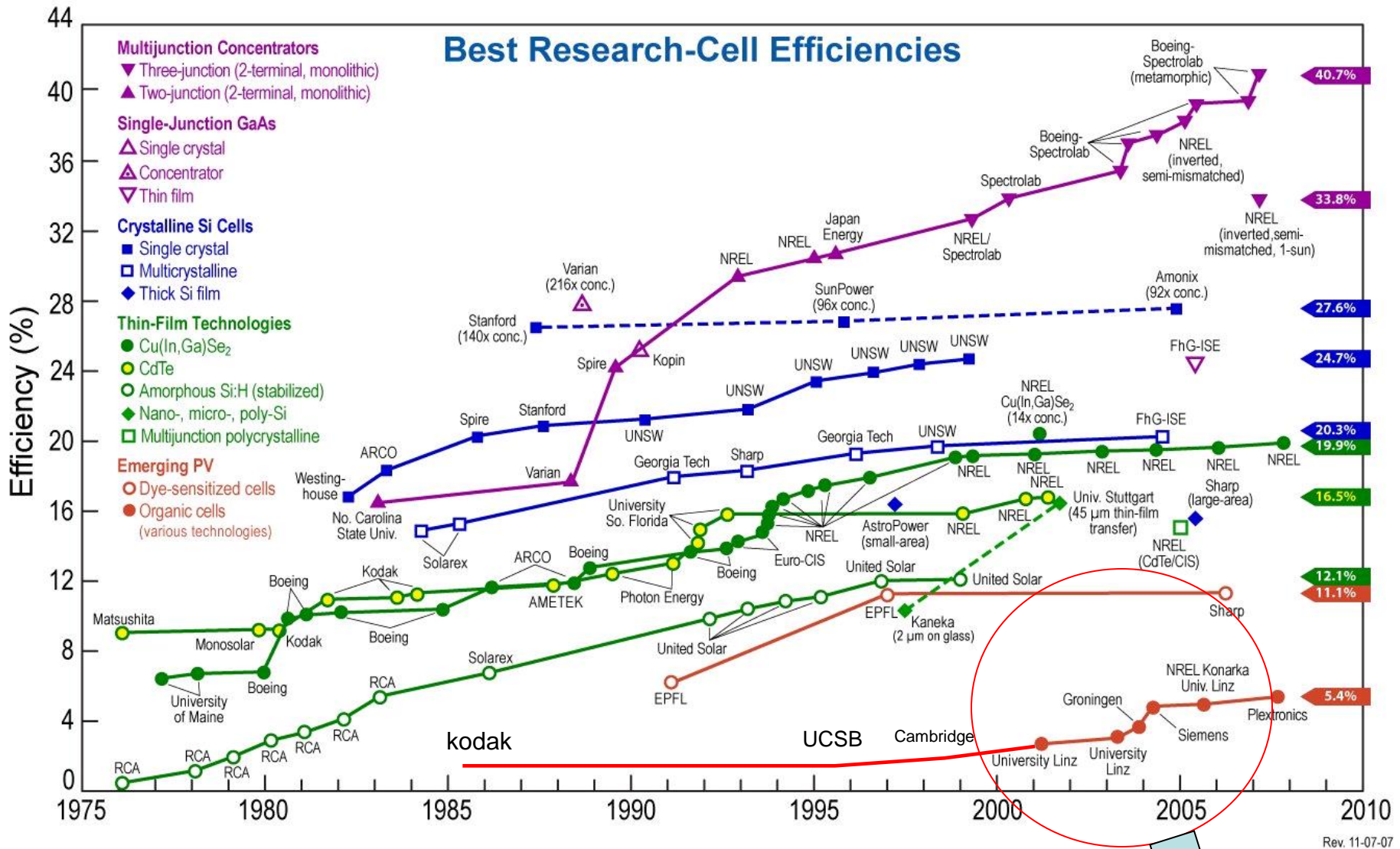
[www.MaterialsViews.com](http://www.MaterialsViews.com)

*Adv. Mater.* 2010, 22, 1–4

## High-Efficiency Solar Cell with Earth-Abundant Liquid-Processed Absorber

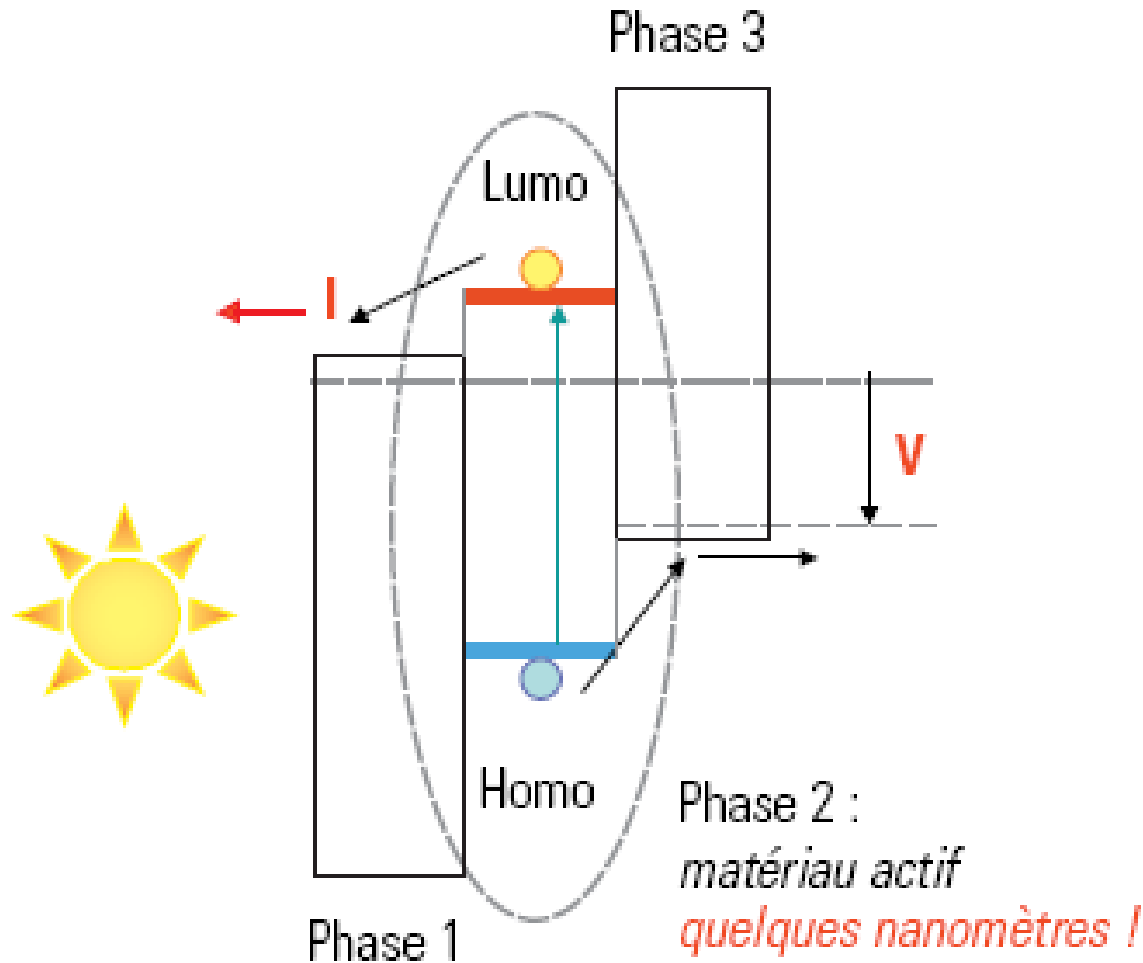
By Teodor K. Todorov, Kathleen B. Reuter, and David B. Mitzi\*

# Les filières émergentes : les nanostructures

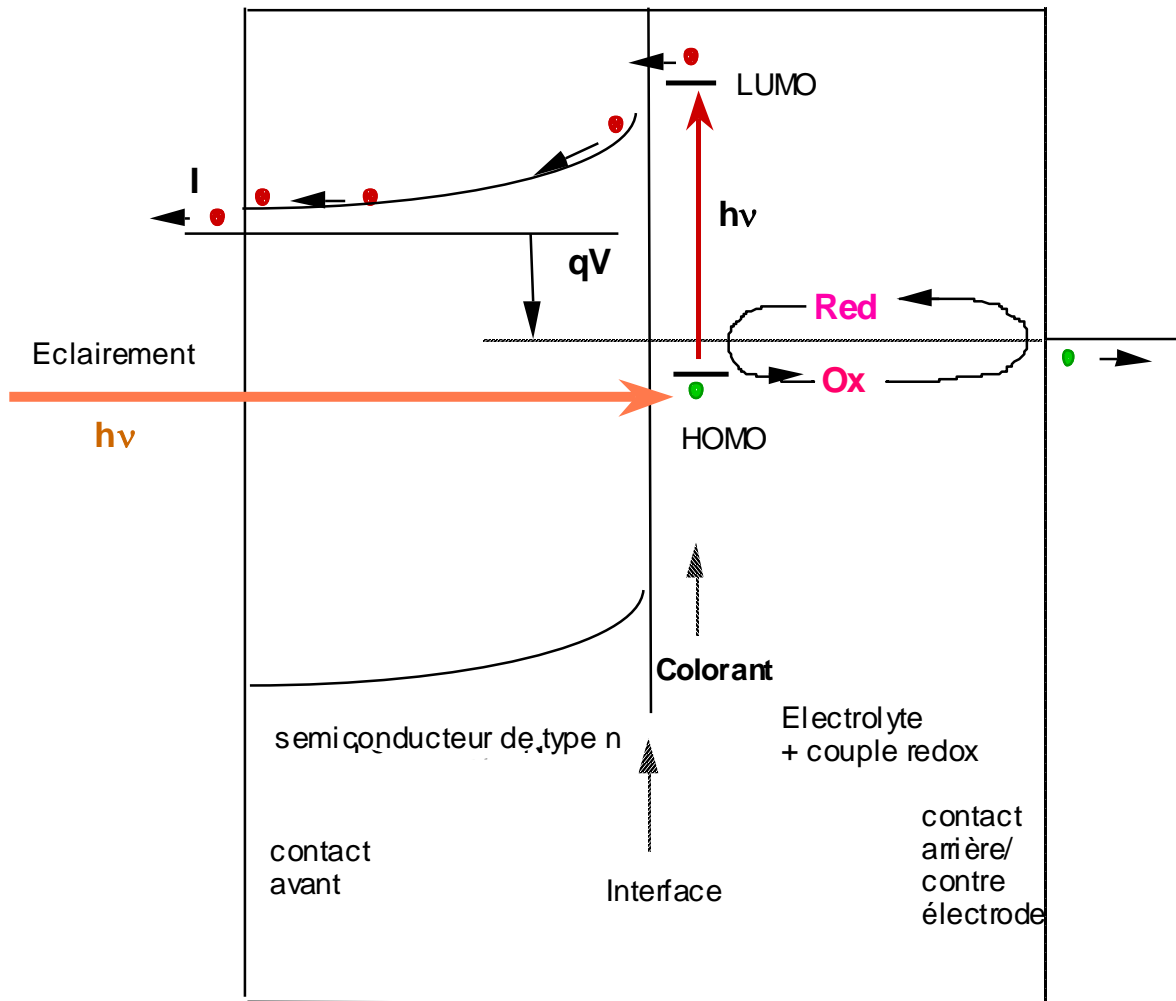


# Un concept révolutionnaire:

## le photovoltaïque moléculaire

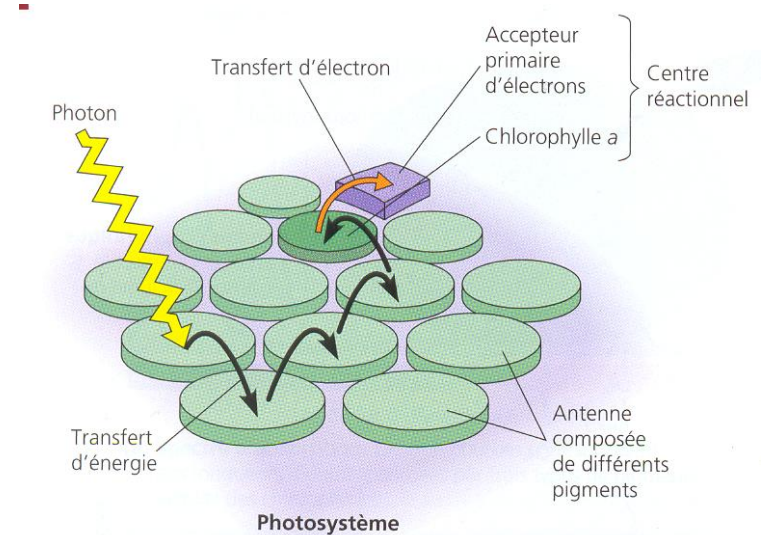
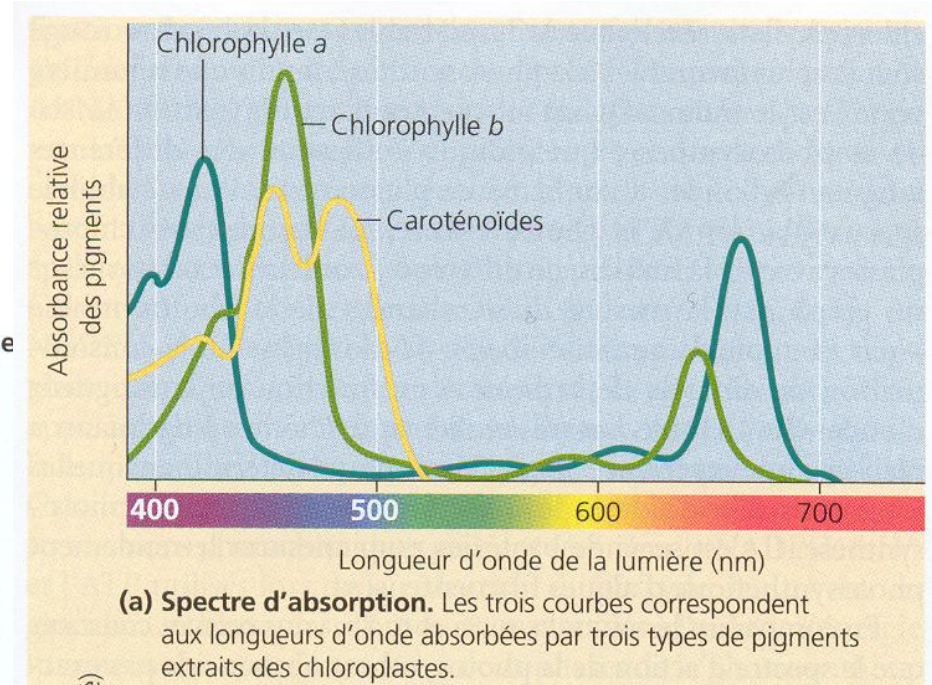
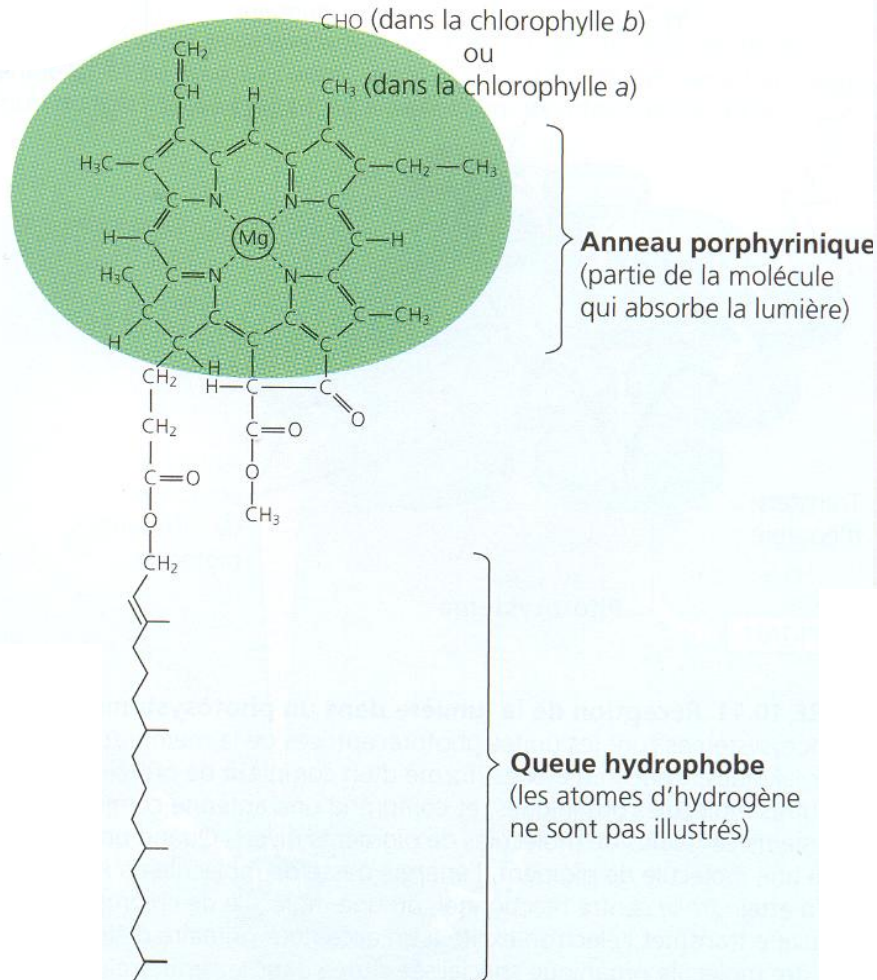


# Effect of Dye adsorption in semiconductor photoelectrochemistry Known for long time (H. Gerischer in the 70's)

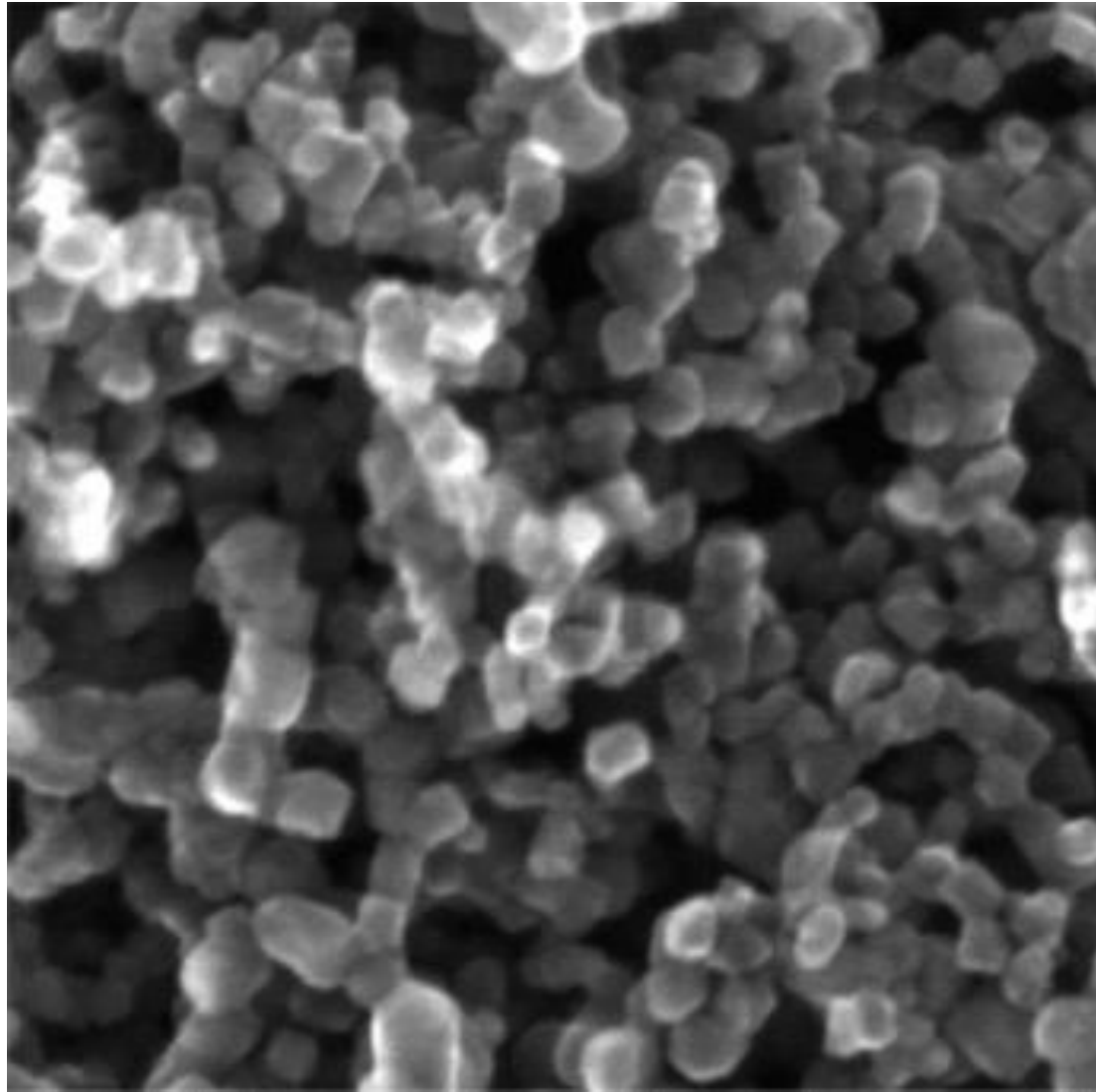


Photocurrent Response detected with high magnification ( $\times 10^4$ ) on flat surfaces

# Natural Photosynthesis

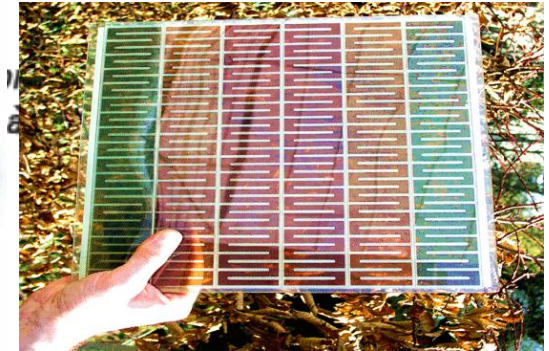
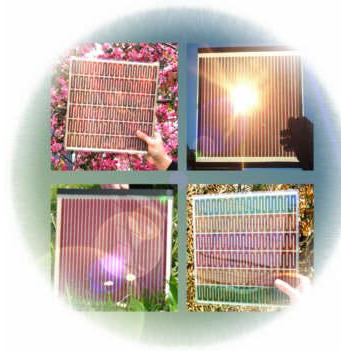
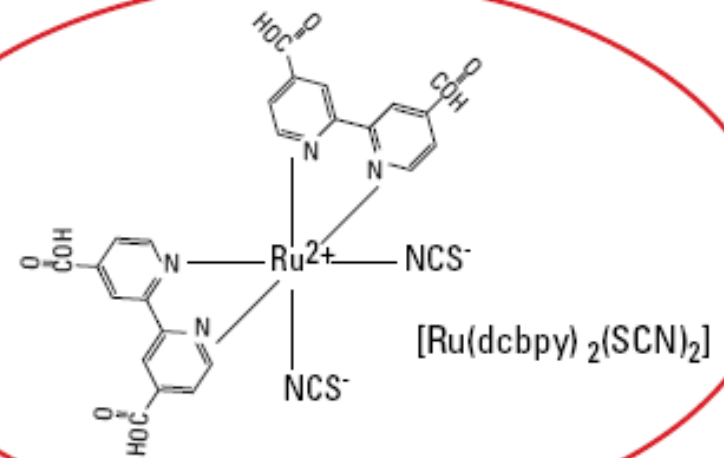
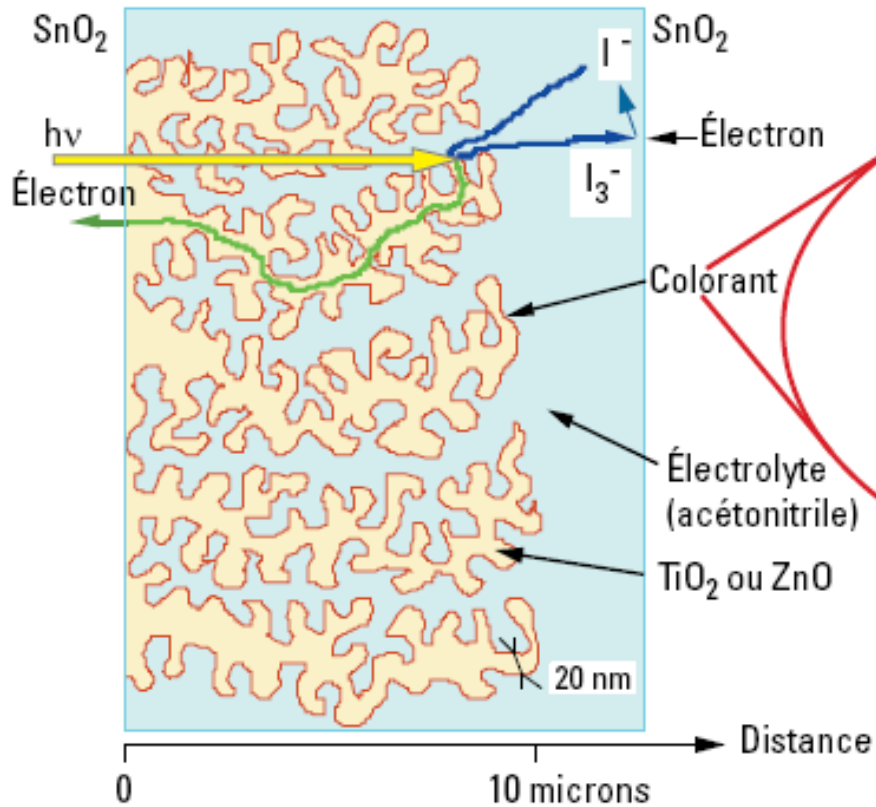


TiO<sub>2</sub>



100 nm

# The Dye Cells named « Graetzel Cells » A Photoelectrochemist's dream



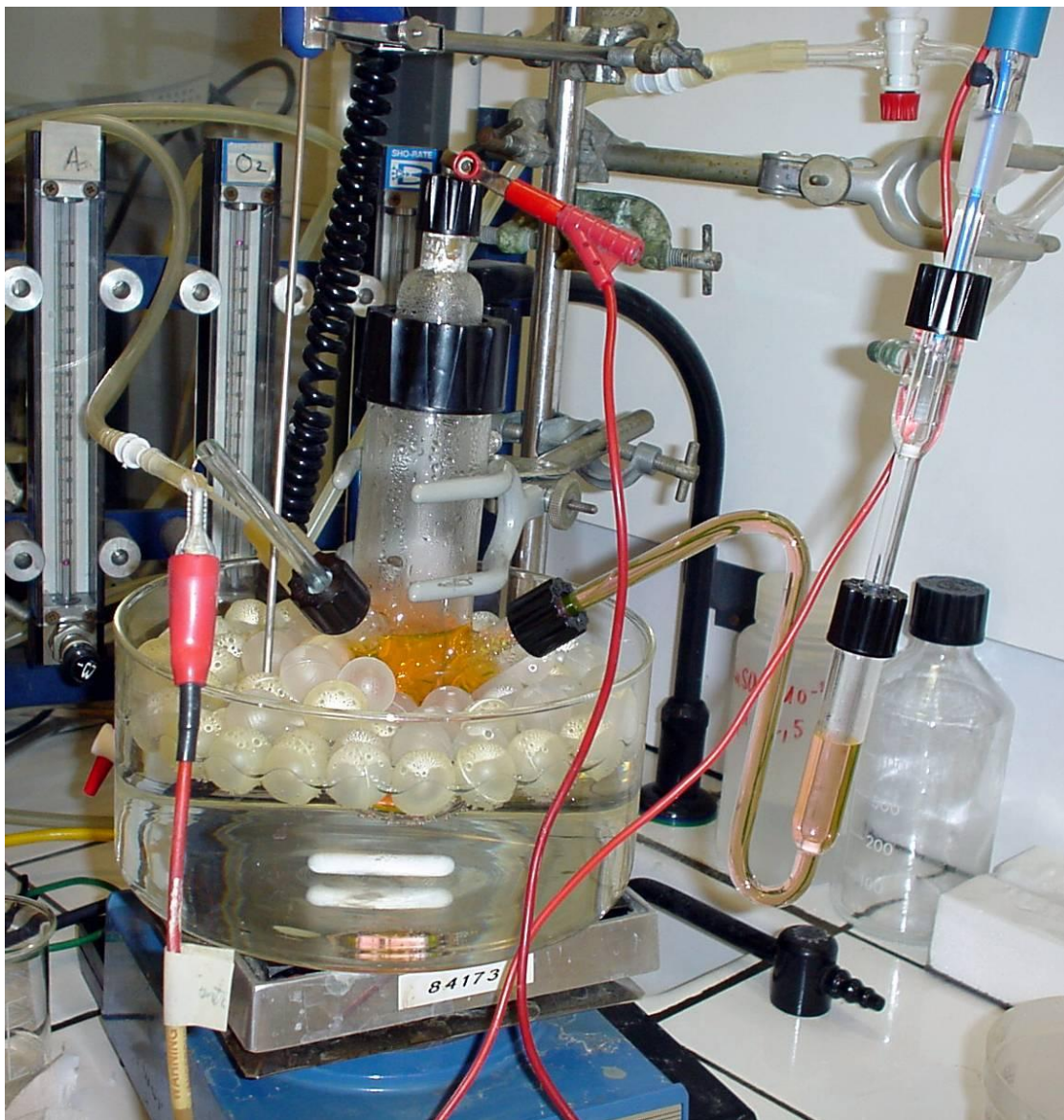


# Synthèse de couches nanoporeuses par électrolyse

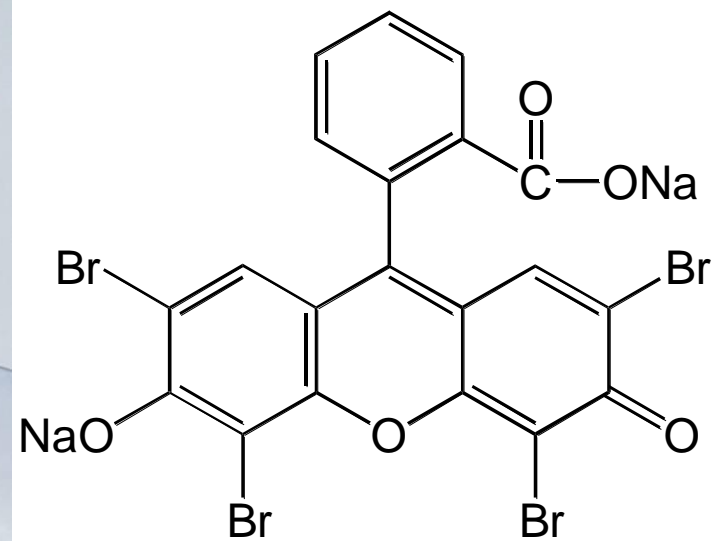


Electrodeposition of ZnO discovered in 1994 at ENSCP

S. Peulon, D. Lincot Adv. Materials 1996

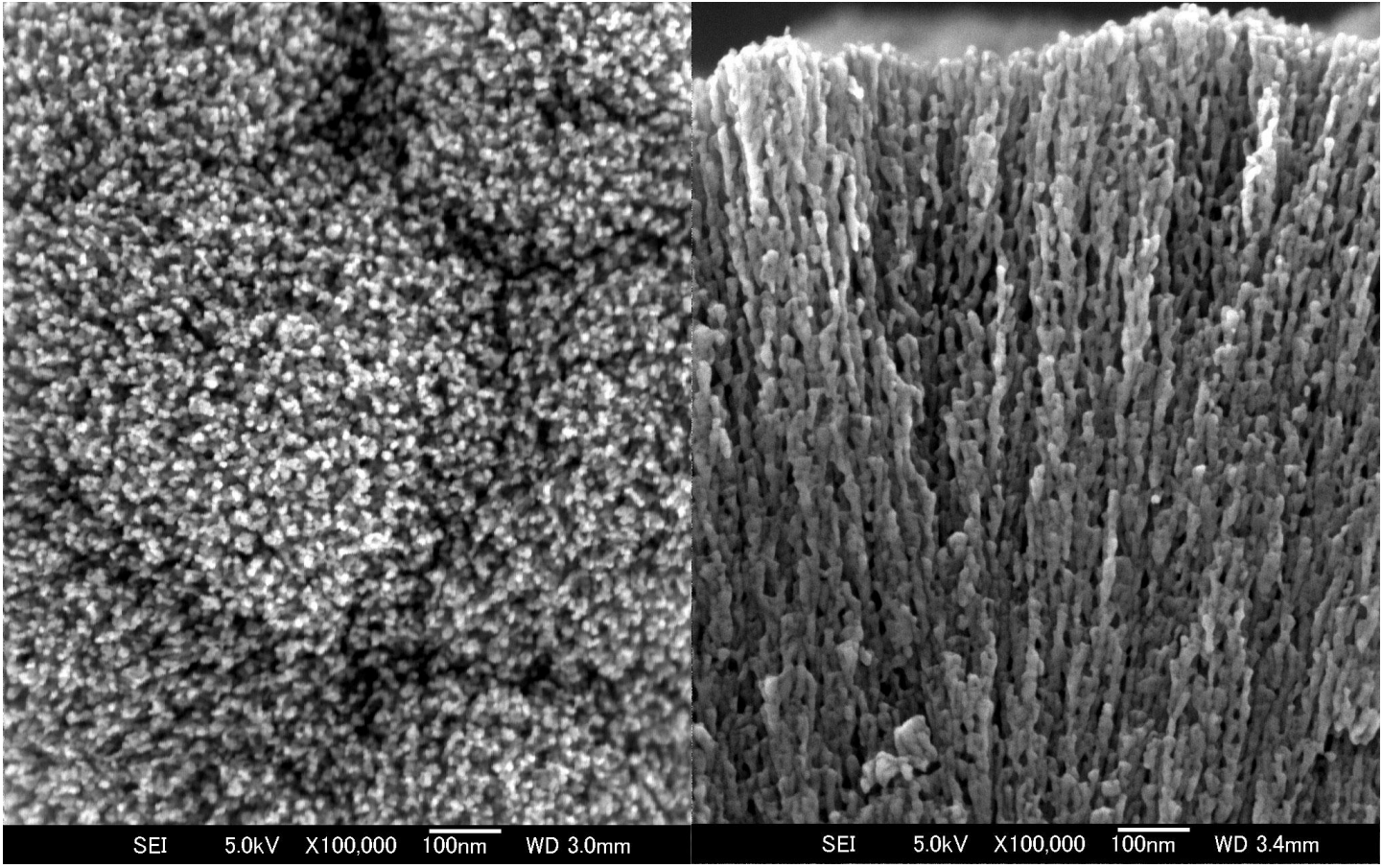


## EOSIN Y



at 0 to 100  $\mu\text{M}$

-1.4 V





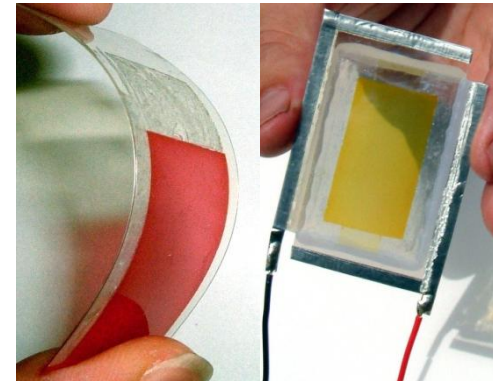
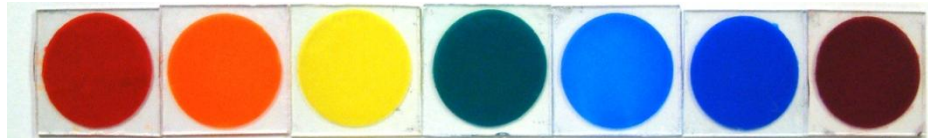
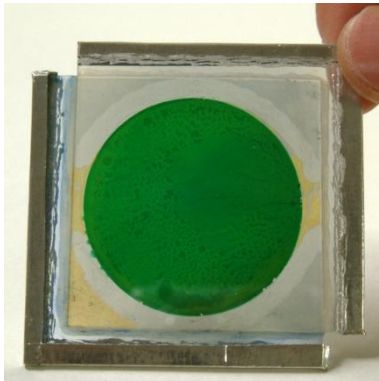
207<sup>th</sup> ECS Meeting, Quebec City, Canada, May 15-20, 2005



**FULL  
COLOR!**



**FLEXIBLE** **SEE THROUGH**



**T. Yoshida,<sup>1</sup> T. Pauporté,<sup>2</sup> D. Lincot,<sup>2</sup> H. Tada<sup>3</sup> and H. Minoura<sup>1</sup>**

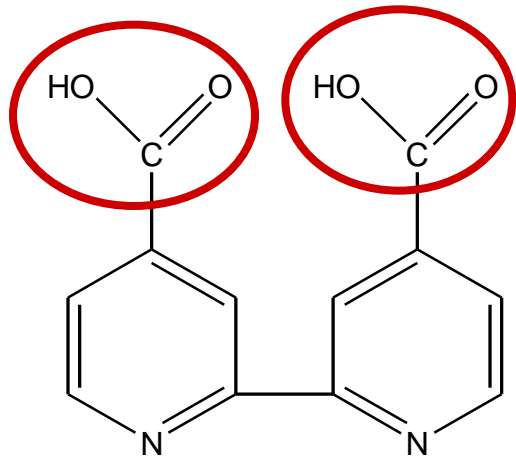
**1; Graduate School of Engineering, Gifu University, Japan**

**2; École Nationale Supérieure de Chimie de Paris, France**

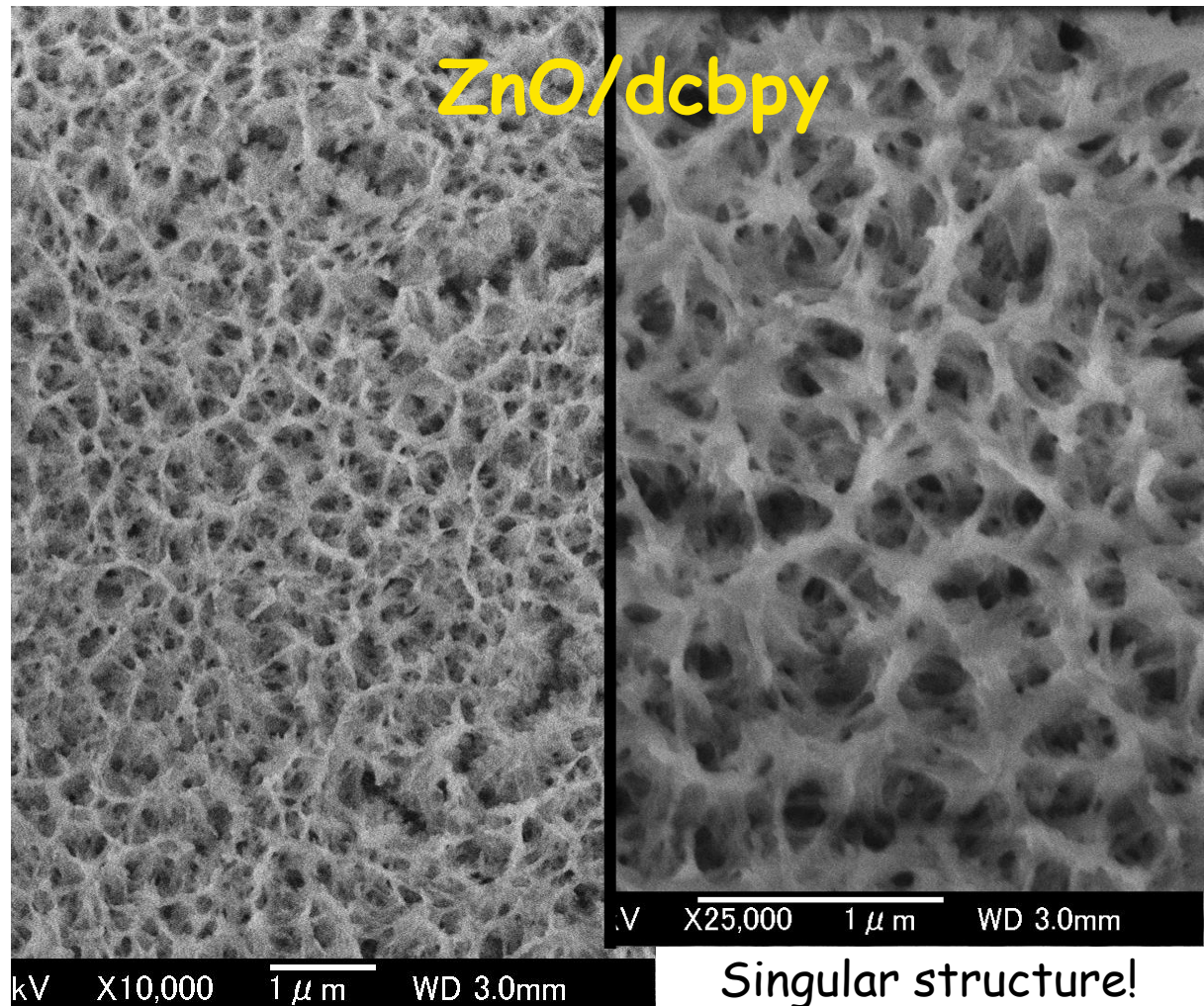
**3; School of Engineering Science, Osaka University, Japan**

Present results : 5.6 % ! T. Yoshida et al. Adv. Functional Materials Submitted

# ZnO Electrodeposition in the presence of 2, 2' - bipyridine 4, 4'-dicarboxylate (dcbpy).



(dcbpy).

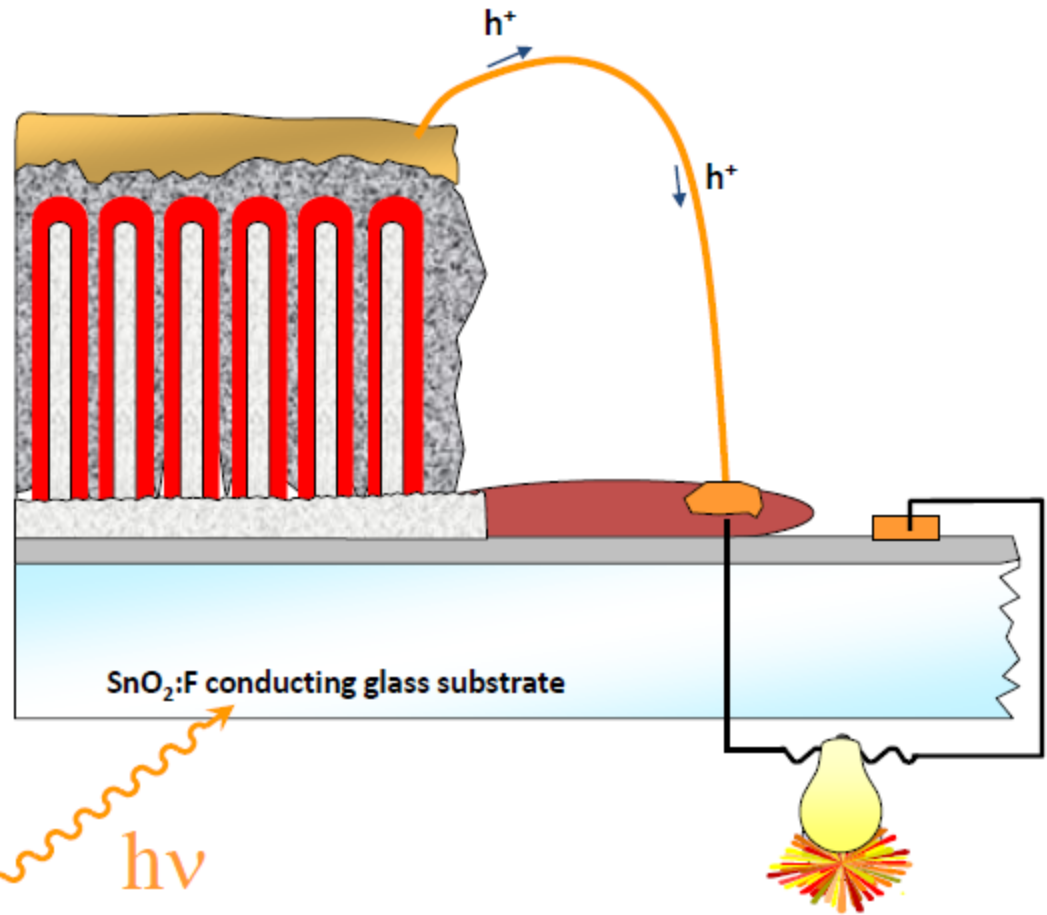


T. Pauporté & T. Yoshida  
Chem. Mat. 2006

# Les cellules inorganiques nanostructurées

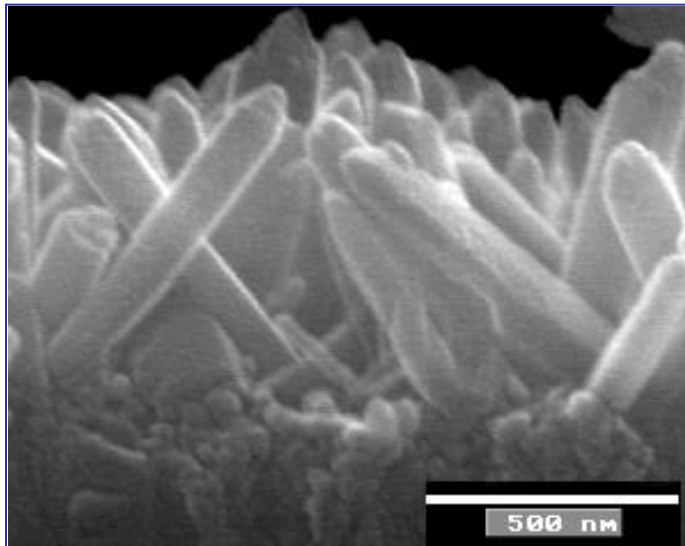
Cellules photovoltaïques ZnO/CdSe/CuSCN de type ETA basées sur un réseau de nanofils de ZnO *Lévy-Clément et al. Adv. Mat. 2005 (Rendement de conversion d'énergie de 2.5 % - facteur de rugosité de ~10)*

1. Couche de ZnO (3.3 eV) déposée par pyrolyse de spray ou ED
2. Dépôt électrochimique des nanofils de ZnO
3. a. Dépôt électrochimique de CdSe (1.7 eV)-30 nm d'épaisseur
4. Dépôt de CuSCN (3.4 eV) type p par infiltration d'une solution saturée
5. Evaporation d'une couche d'or (contact)
6. Isolation du substrat
7. Contacts sur Au et SnO<sub>2</sub> pour mesures

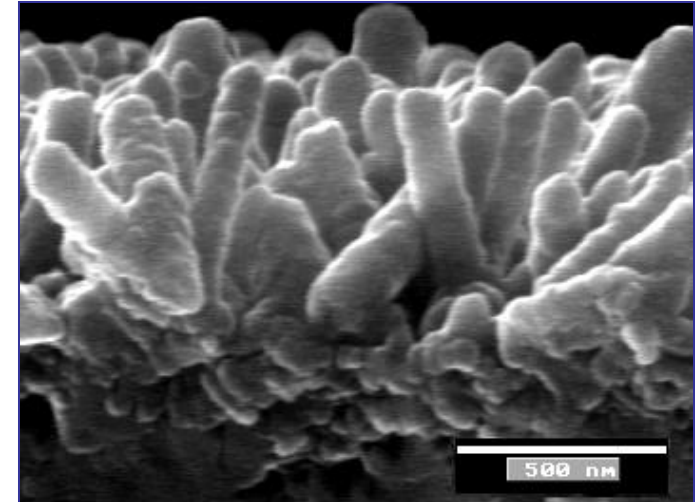


Augmentation du facteur de rugosité →  
Agir sur la densité, le diamètre et la longueur des nanofils

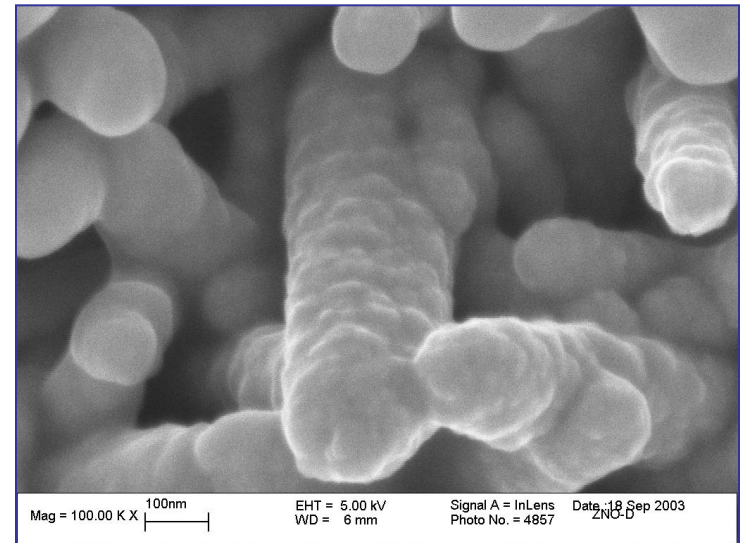
# ELECTRODÉPOSITION de CdSe sur ZnO



CdSe déposition



Formation de ZnO/CdSe  
nanofils Cœur-enveloppe  
Épaisseur 30 nm CdSe





# Cellules organiques

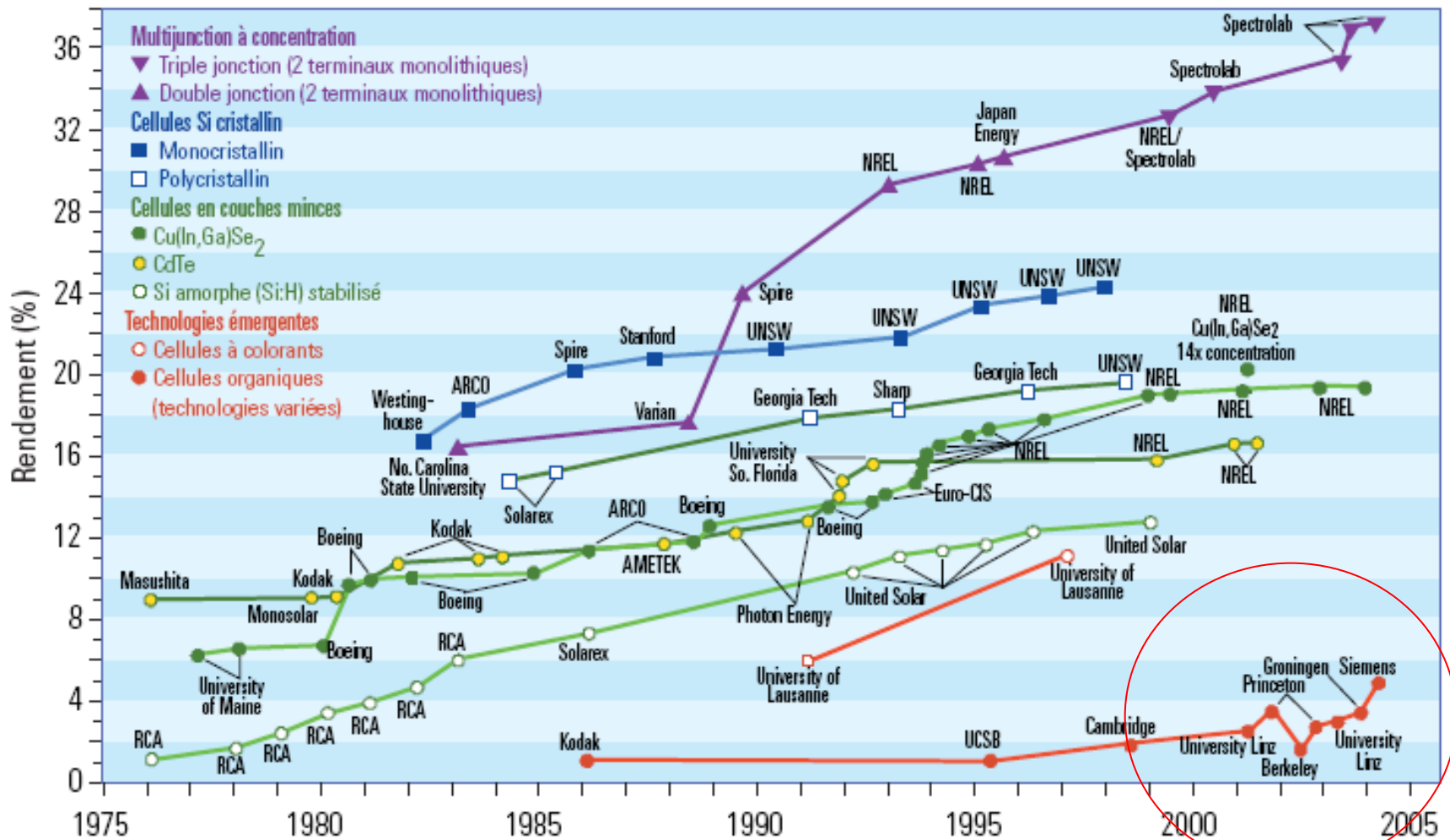
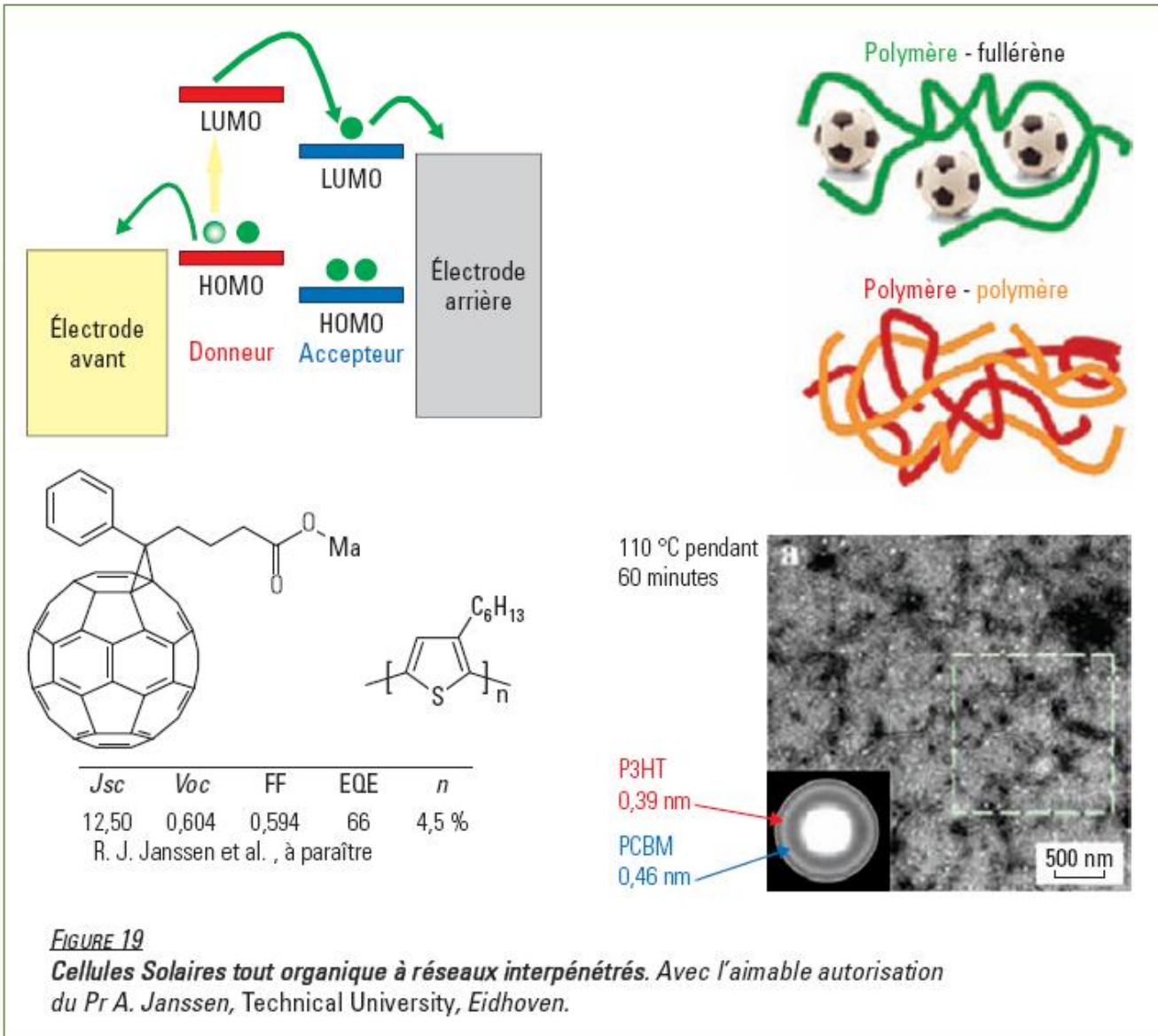


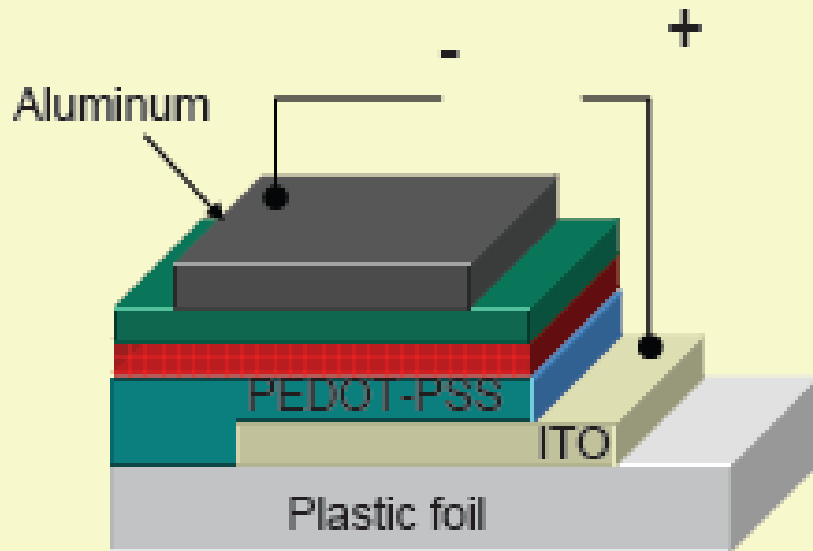
FIGURE 10

Rendements photovoltaïques record. Source NREL, [www.nrel.gov](http://www.nrel.gov).

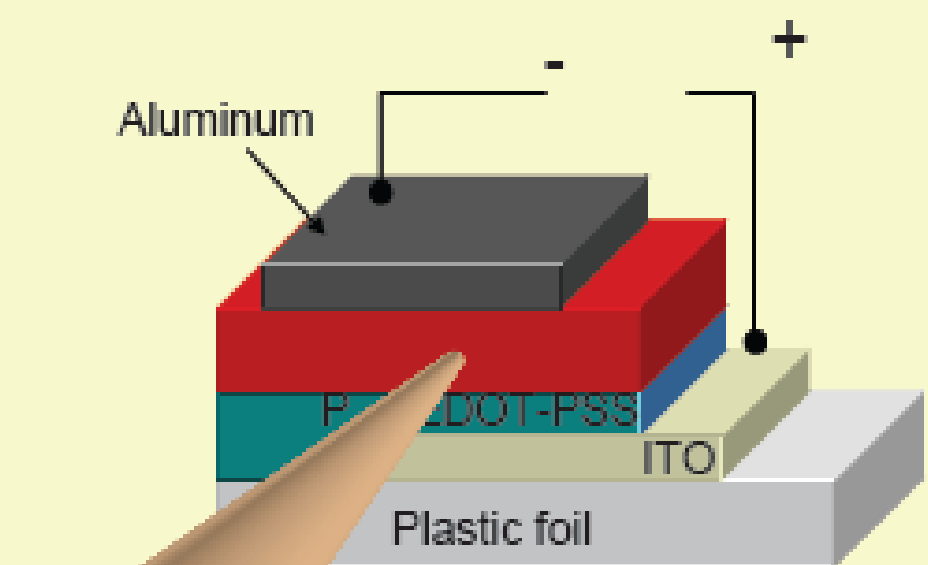


Thanks to Prof. Janssen

## BILAYER



## BULK HETEROJUNCTION

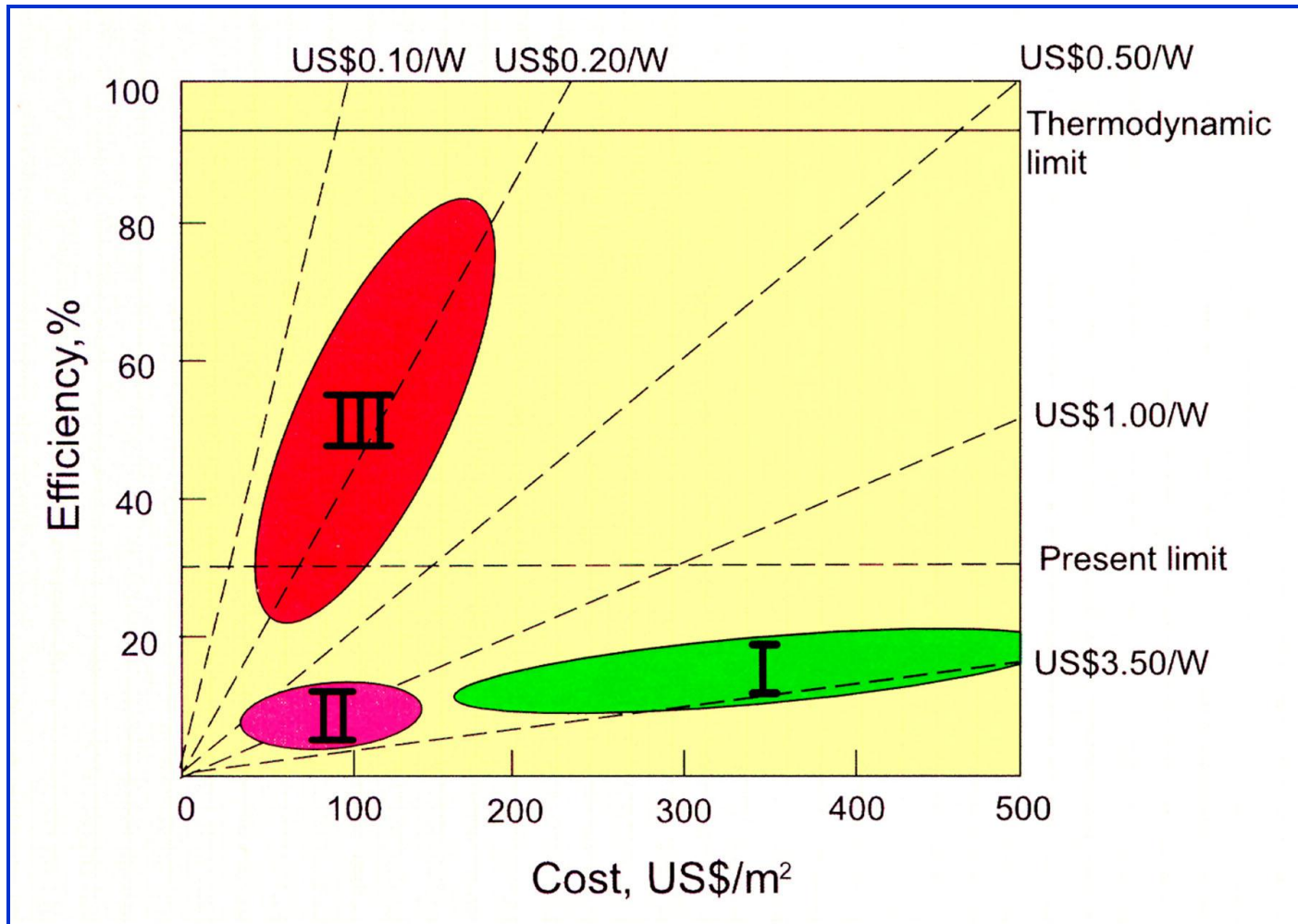


Thanks to Prof. Saricifti

Au delà des 30%

Les concepts Photovoltaïques très  
hauts rendements

# L'espace stratégique du photovoltaïque

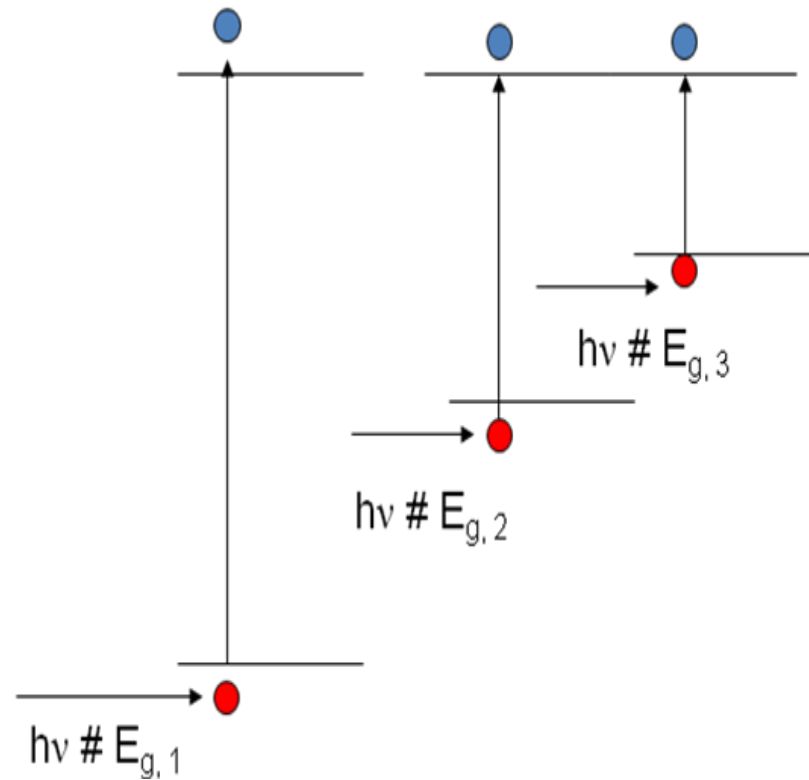
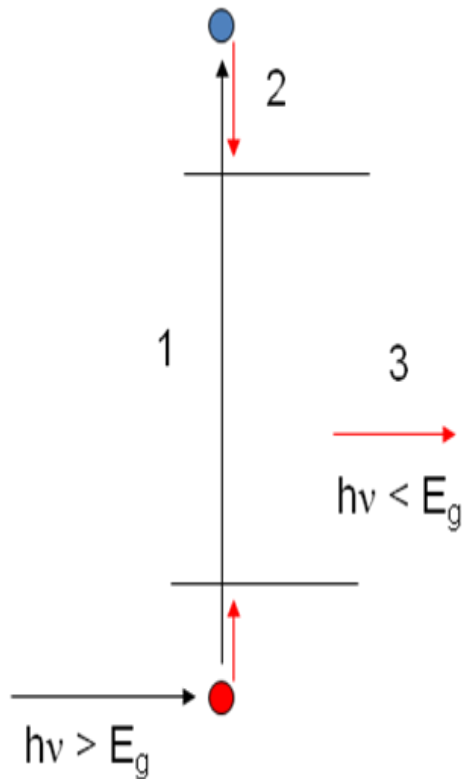


I- Silicium Cristallin

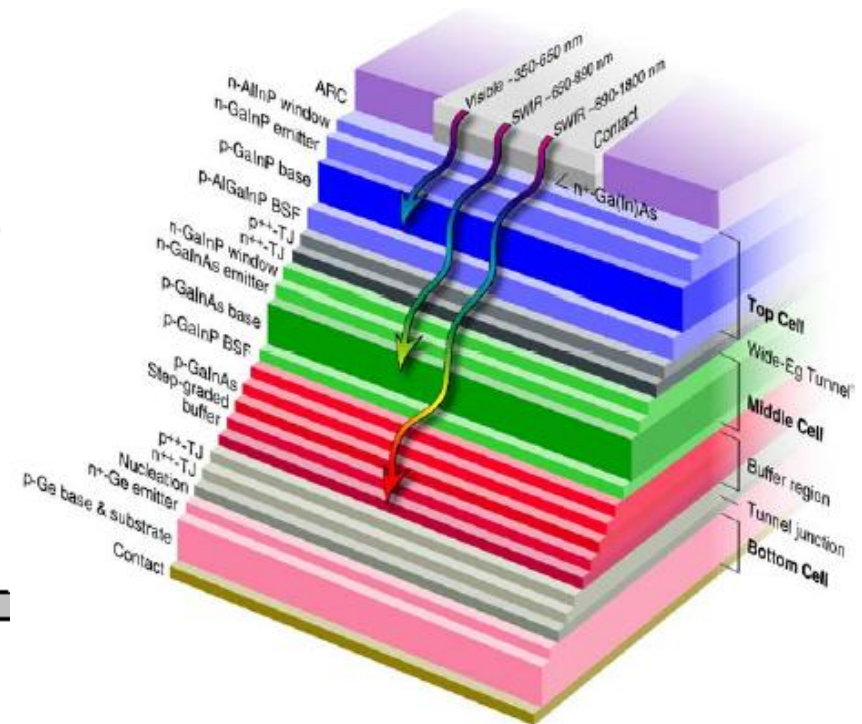
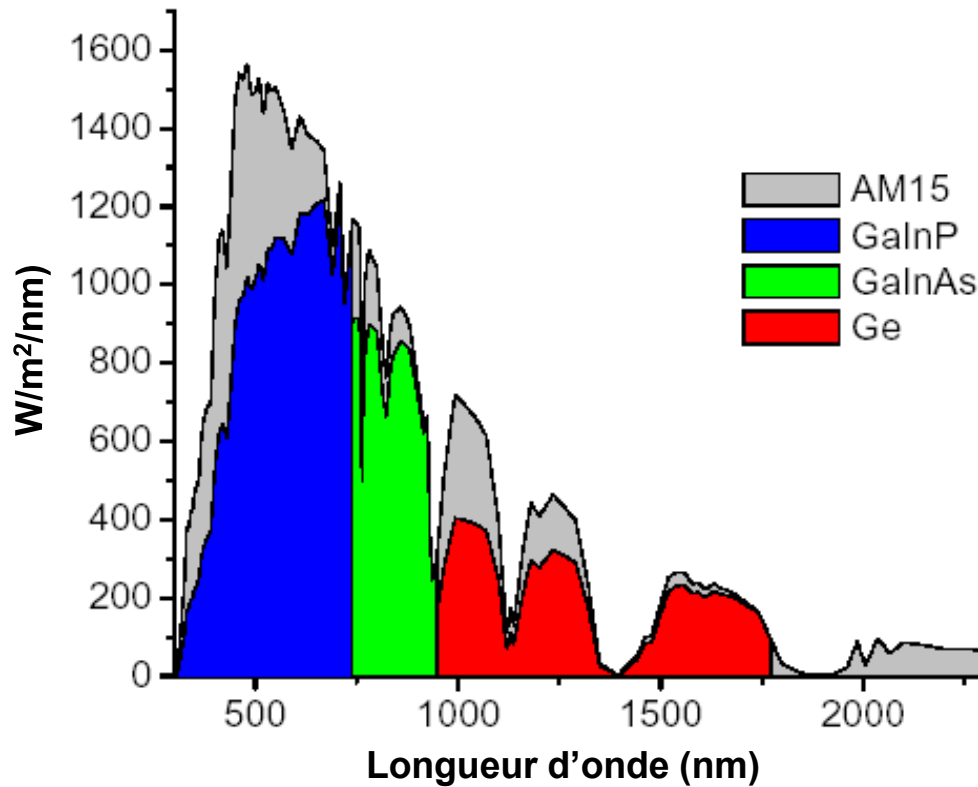
II- Couches minces

III- Multijonctions et nouveaux concepts (= I + II + X)

# Les hauts rendements : l'approche multijonctions

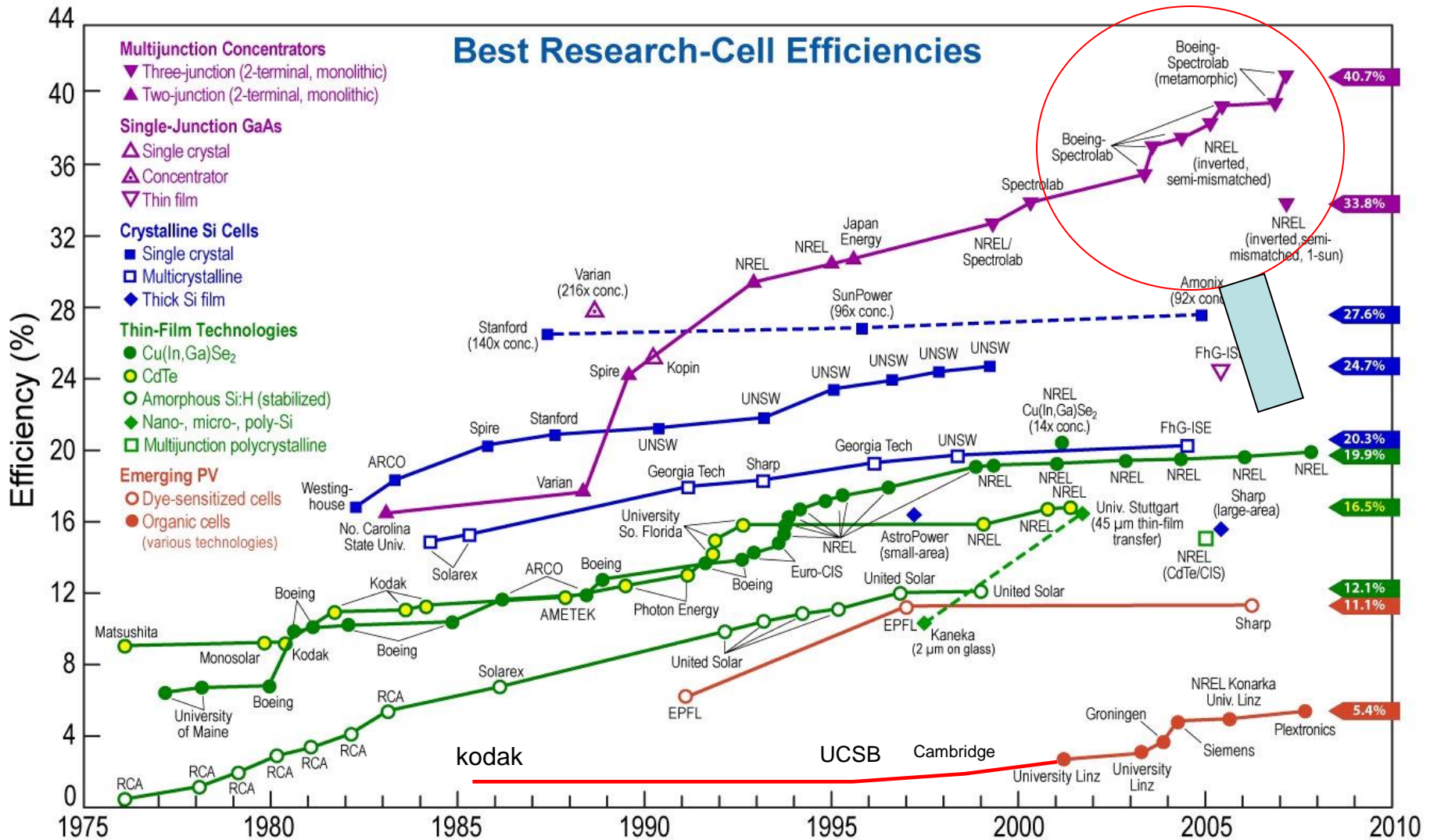


# De la théorie...à la pratique !





# Les différentes filières photovoltaïques



# Nouveaux concepts très hauts rendements > 50%

- Conversion de photons

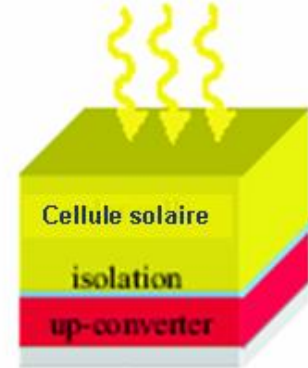
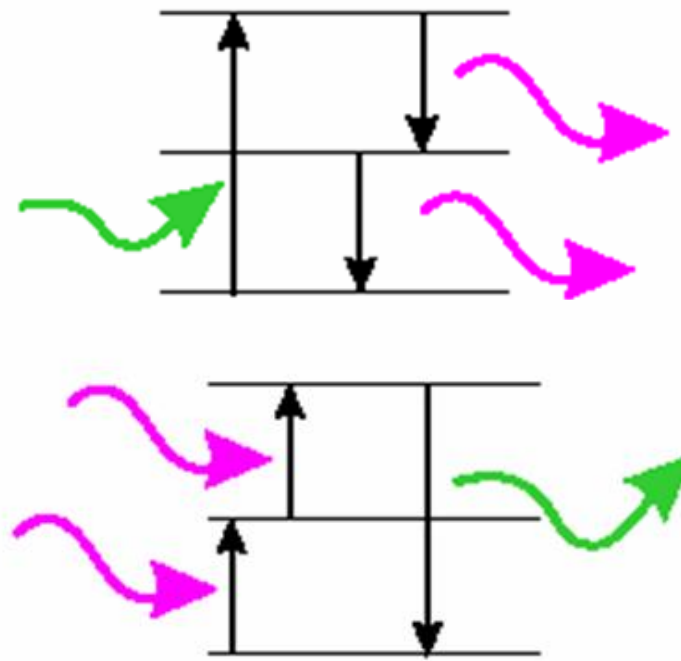
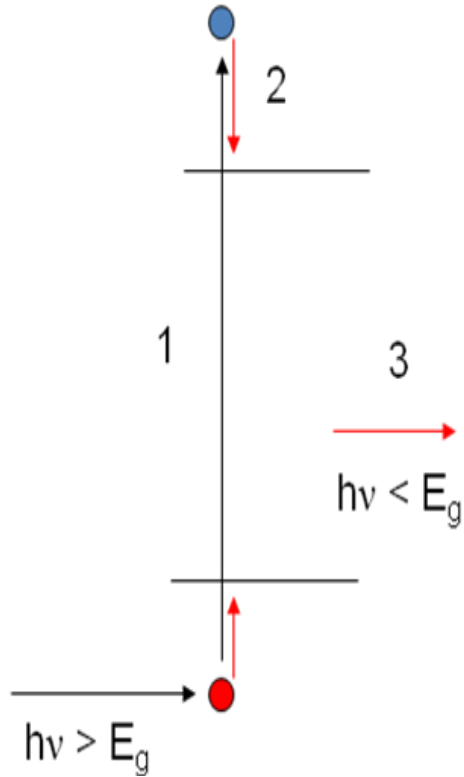
  - « Up Conversion », « down conversion »

- Porteurs chauds

- Bandes intermédiaires

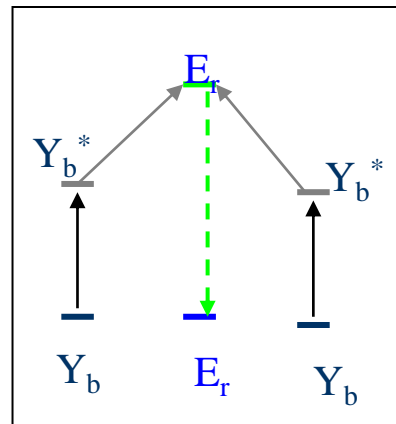
  - « photovoltaïque de spin »

# Conversion de photons

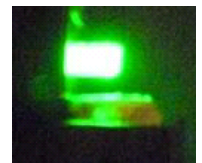
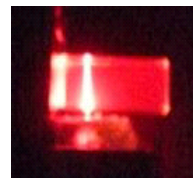
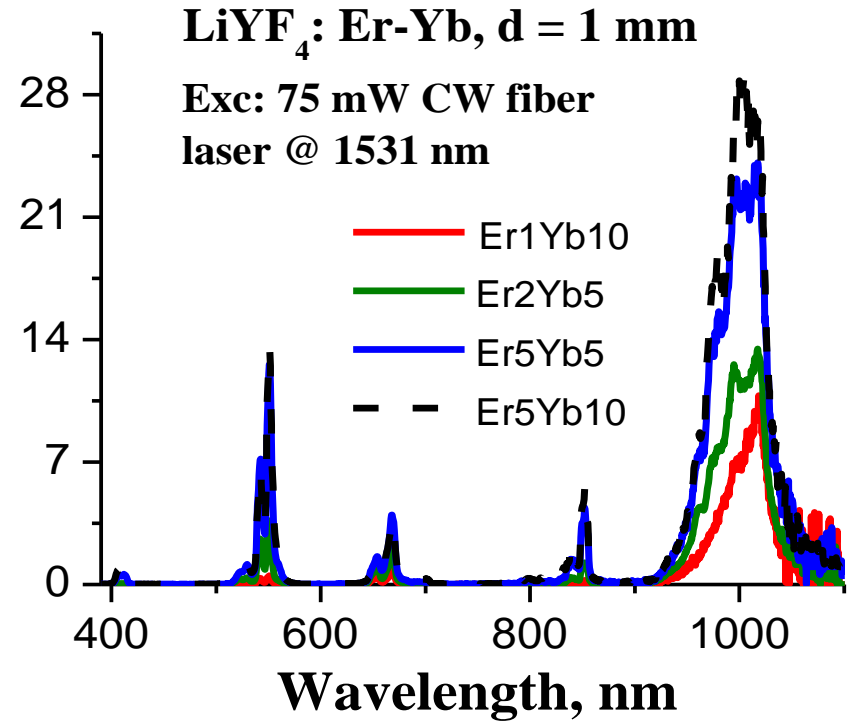
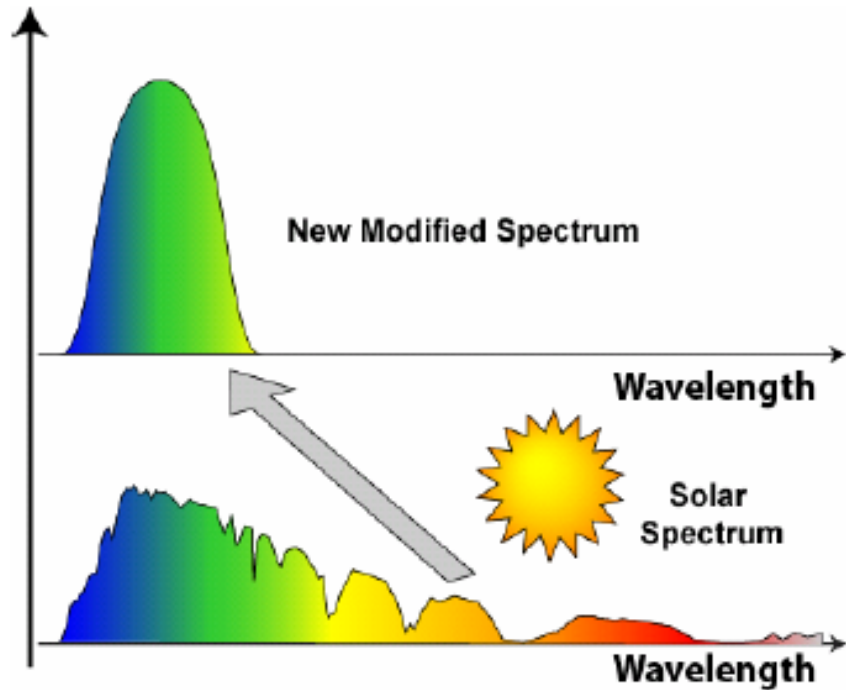


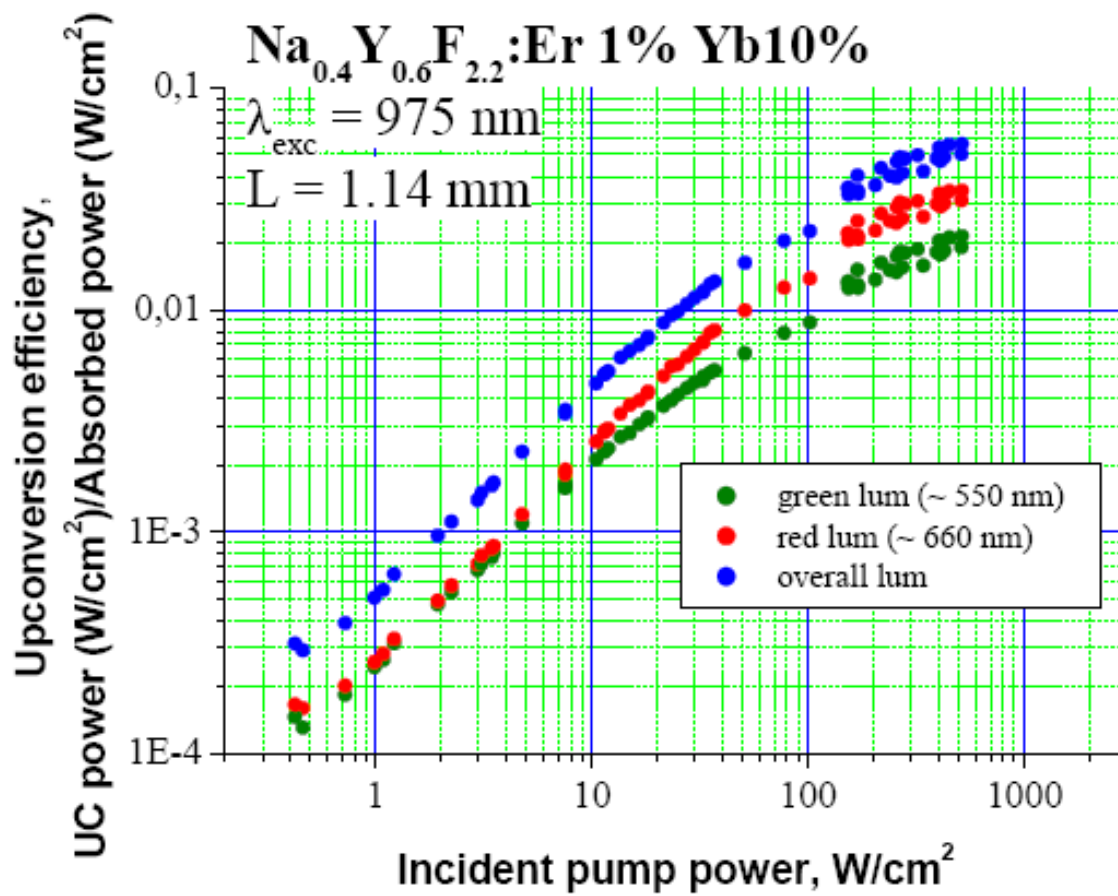
oxydes, fluorures  
Dopage terres rares

(ex:  $\text{NaYF}_4$ )

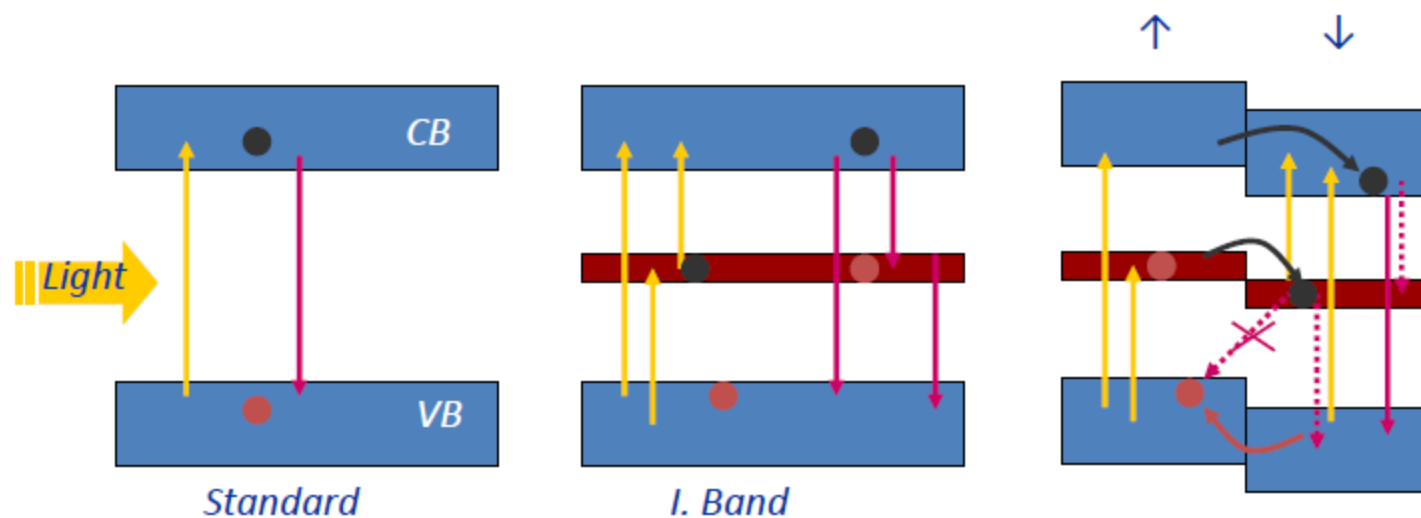


# Du rêve à la réalité





# Photovoltaïque de spin J.F. Guillemoles et al PRL (2005)



	$\eta_{max}$	$T_C$	$\Delta E_{FM-AFM}$	$E_1$ (eV)	$E_2$ (eV)	$E_g$ (eV)	$\Delta E_g$
<b>GaN</b>							
$Cr_{Ga}$	40 %	140 K	-0.16 eV	2.05	1.03	3.28	0.01
$Mn_{Ga}$	42 %	120 K	-0.15 eV	1.84	0.97	3.06	-0.22

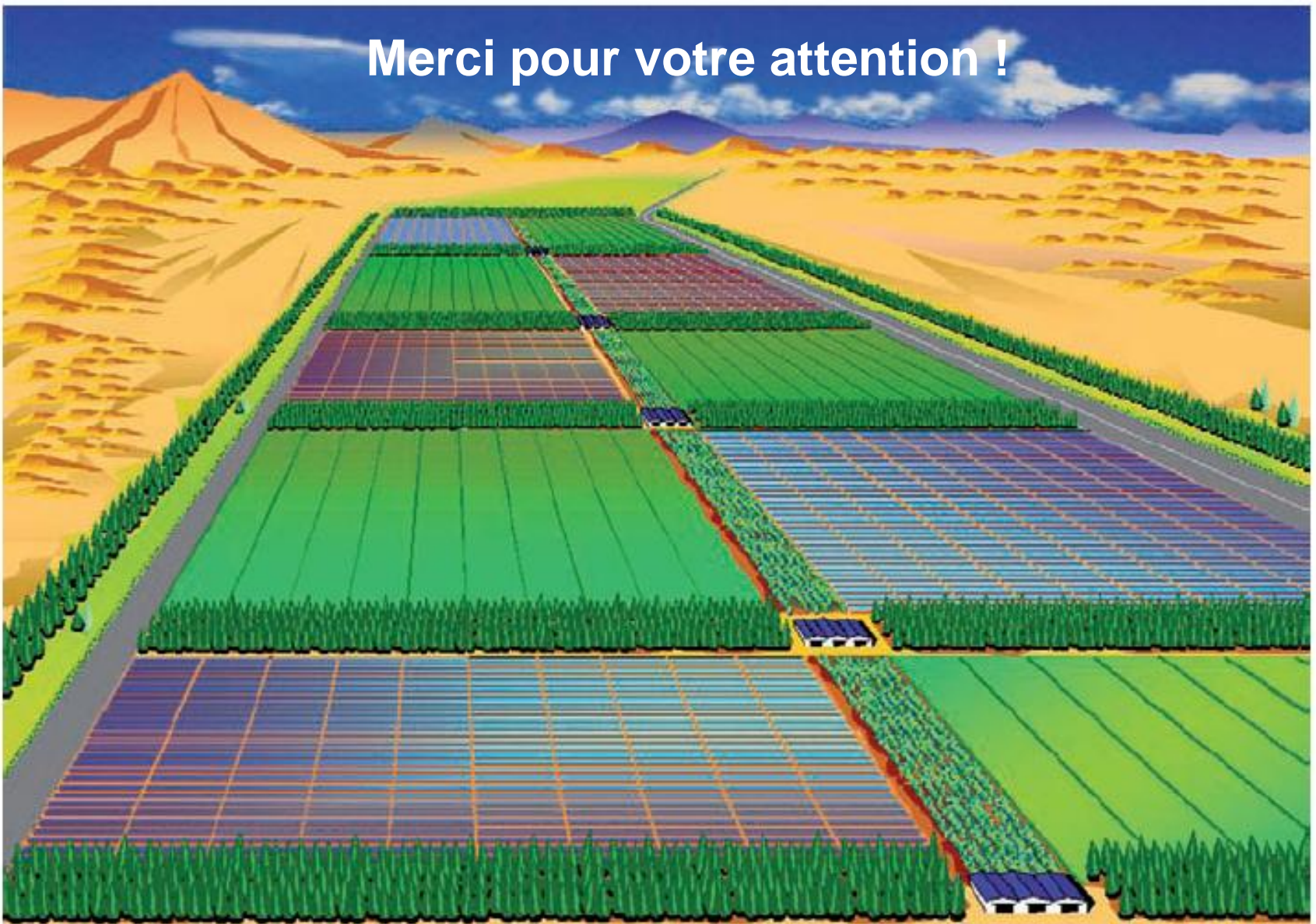
	$\eta_{max}$	$T_C$	$\Delta E_{FM-AFM}$	$E_1$ (eV)	$E_2$ (eV)	$E_g$ (eV)	$\Delta E_g$
<b>CuGaS<sub>2</sub></b>							
$Co_{Cu}$	43 %	68 K	-0.08 eV	1.40	0.66	2.33	-0.16
$Cr_{Ga}$	44 %	114 K	-0.15 eV	1.59	0.46	2.48	0

# Conclusions

« La conversion photovoltaïque de l'énergie solaire  
Un extraordinaire défi pour les chimistes »

- Matériaux
- Méthodes de synthèse
- Architecture des dispositifs
- Concepts hauts rendements

**Merci pour votre attention !**



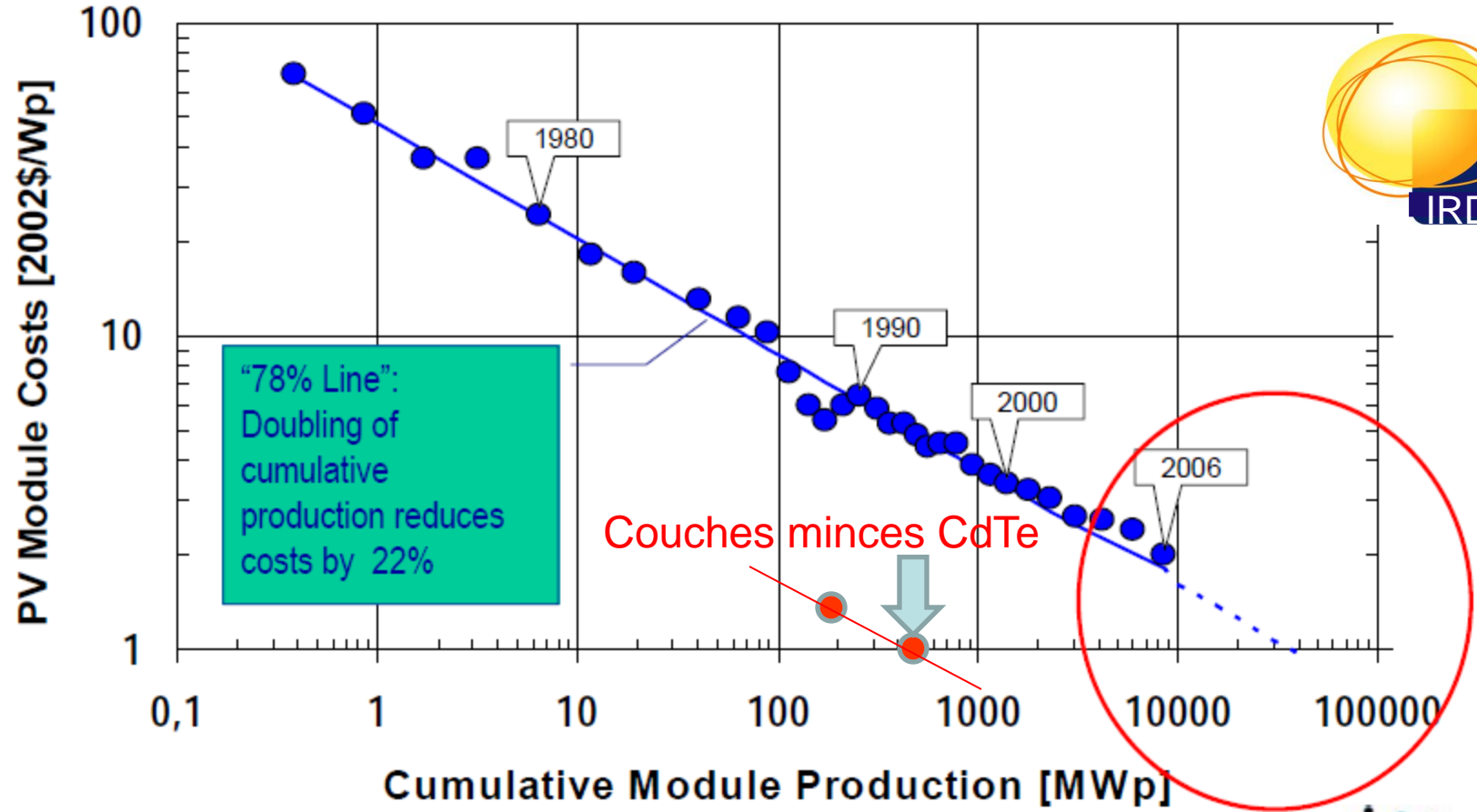
*FIGURE 20*

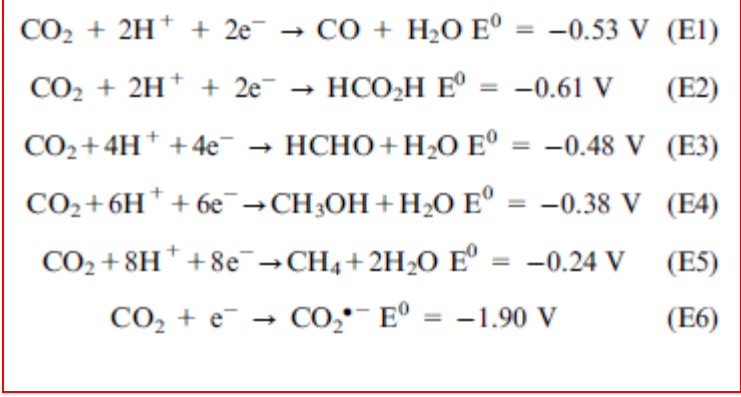
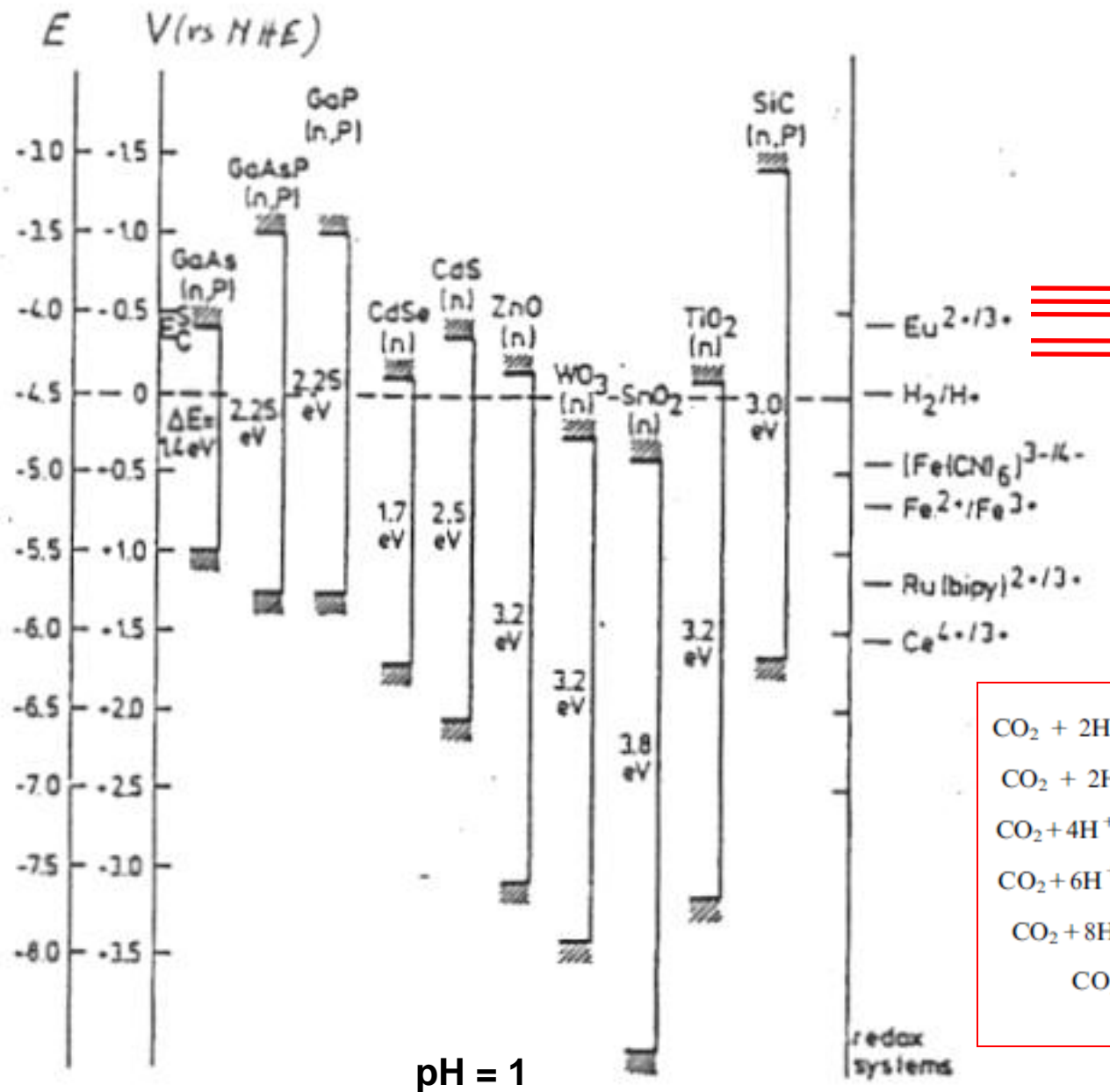
*Une prospective japonaise : l'énergie photovoltaïque à très grande échelle (Very Large Scale Photovoltaics).  
Source : Energy from the desert, Feasibility of a very large scale photovoltaic generation systems (VLS-PV)  
Ed. K. Kurokawa, James & James, 2003.*



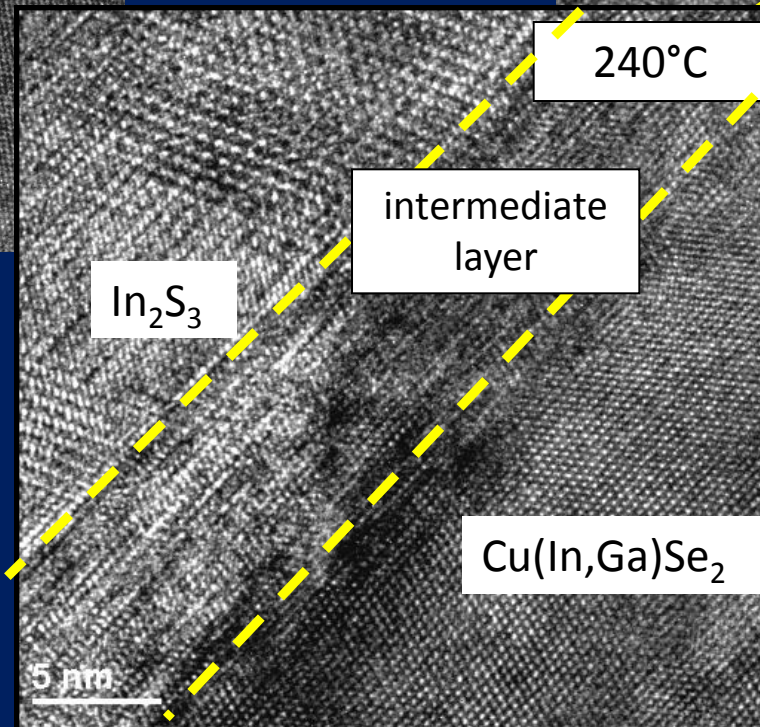
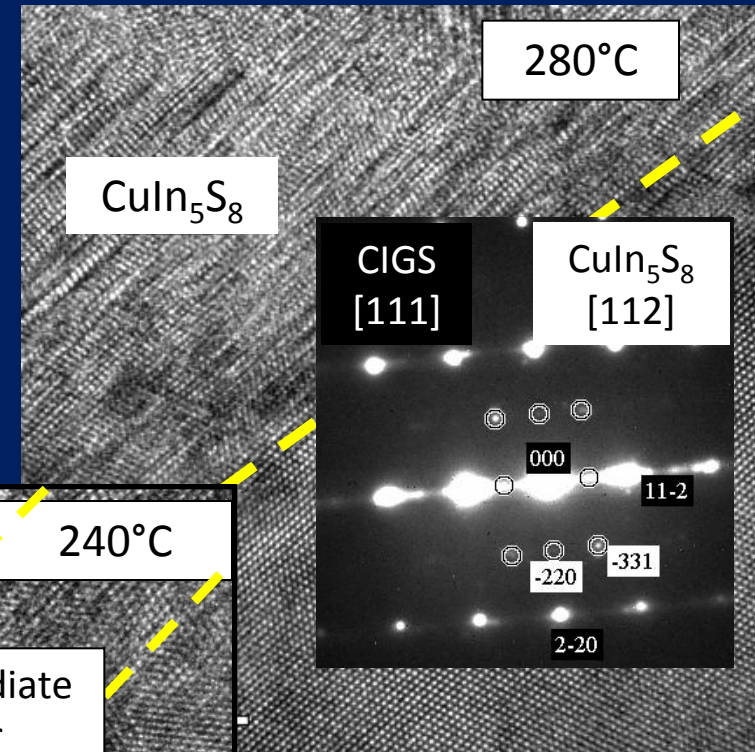
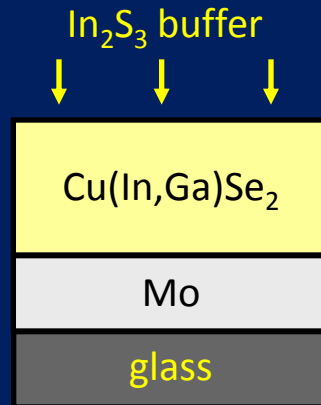
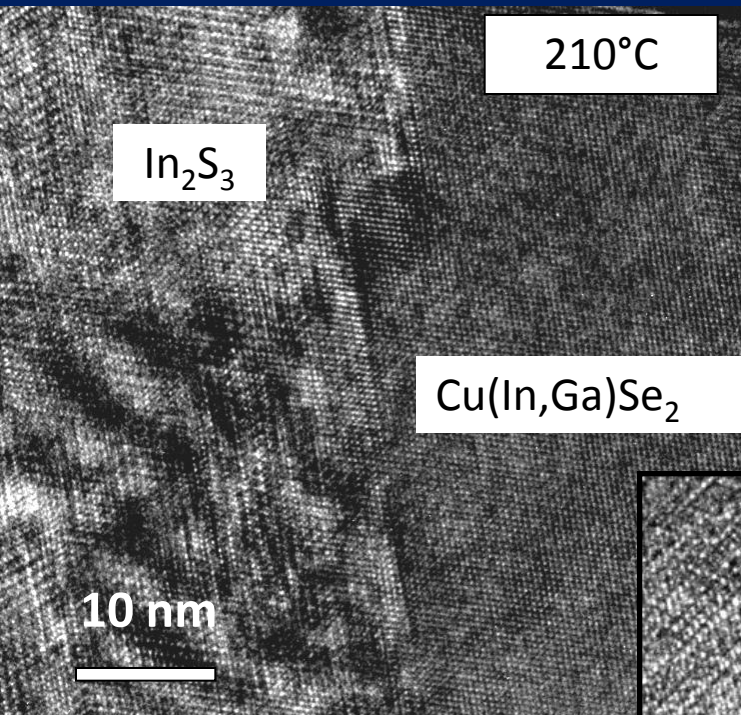


# PV Technology Learning Curve since '76





# Remplacement du CdS par de l' $\text{In}_2\text{S}_3$ (par ALCVD)



Abou-Ras et al., JAP 97(8) & JAP 98(12) (2005)