

À la recherche des performances ultimes pour la conversion photovoltaïque

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■ 9 février 2022



Auto-introduction



L'IPVF: un centre de recherche et de valorisation:

Partenariat public-Privé

(Institut de la transition énergétique)

200 personnes, 8000 m² à Palaiseau



Jean François Guillemoles, Chercheur CNRS,
Directeur de l'UMR de l'Institut Photovoltaïque
d'Ile de France (IPVF),

Pr chargé de cours à l'X

CV : <https://cv.archives-ouvertes.fr/jean-francois-guillemoles>
https://www.researchgate.net/profile/Jean_Francois_Guillemoles



Remerciements

FedPV

C2N: S. Collin, A. Cattoni, A. Delamarre, Hung-Ling Chen, ...



FOTON: S. Richard, A. Lecorre, O. Durand

GEEPS: JP Kleider, Z. Djebbour, J. Connolly

IMN: N. Barreau

IM2NP: N. Cavassilas, F. Michelini, ...

Icube: Th. Fix A. Slaoui

ILV, INL, LMGP, IRCP, IPHC, LCMCP,...

ECOLE des HOUCHES

(application : <https://sunlit-team.eu/pv-school-2022/application/>)



D. Lincot, L. Lombez, D. Suchet, AL Joudrier, N. Schneider, P. Schulz, N. Naghavi, G. Delpont, B. Berenguier, A. Rebai, N. Loones, J. Rousset, N. Vandamme, Julie Goffard, D. Ory, A. Bercegol, M. Legrand, G. Vidon, T. Vezin, A. Py-Renaudie, A. Julien, Mayhar, D. Micha, ...

et IRDEP: Trung Dac Nguyen, F. Gibelli, J. Rodière, C. Crevant, A. Lebris, M. Paire, C. Andriamiadamanana, S. Ivanovna, S. Laribi, J. Vidal, P. Olsson, C. Domain, ...

International:

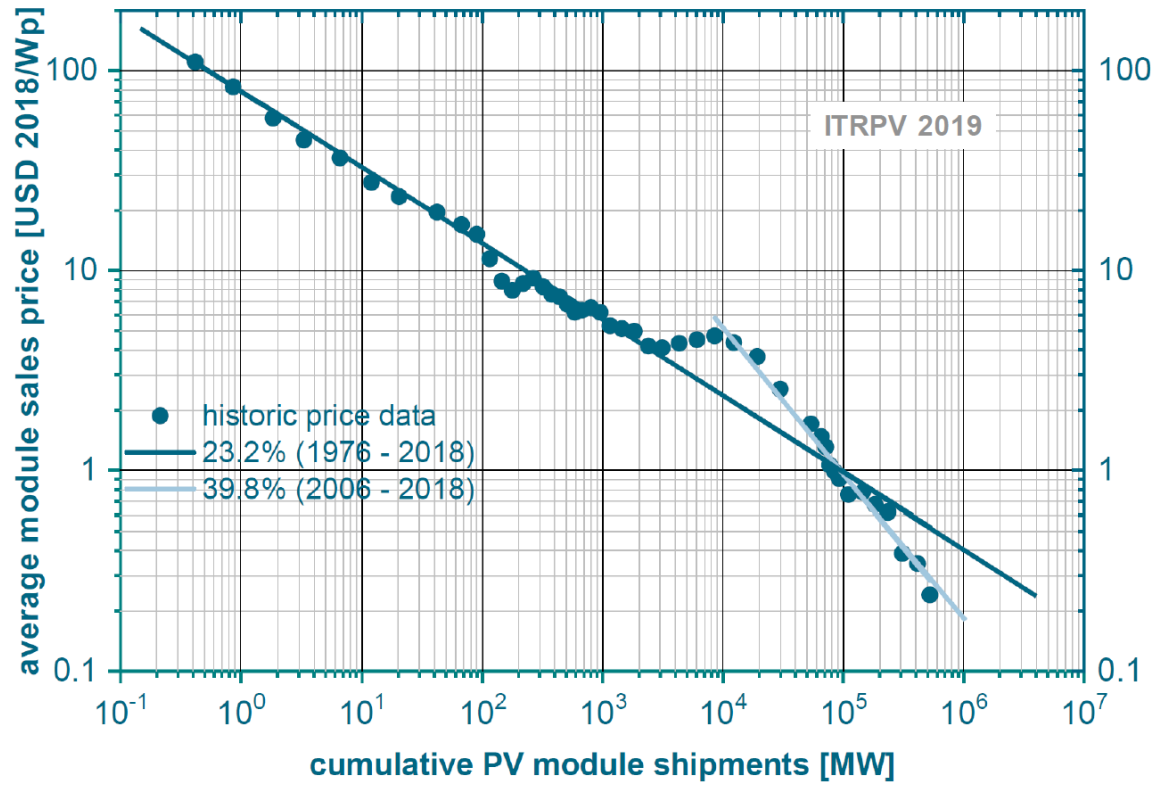
Julich (U. Rau), WIS (D. Cahen), ASU (S. Goodnick), UNSW (G. Conibeer, M.A. Green), Imp. College, U. Oklahoma, HZB (D. Abou Ras, HW Schock, ...), U. Huston (A. Freundlich), ISE, ...



Y. Okada, M. Sugiyama, T. Kubo, H. Segawa, M. Giteau, B. Behaghel, Z. Jehl, T. Bidaud, S. Almosni, ...



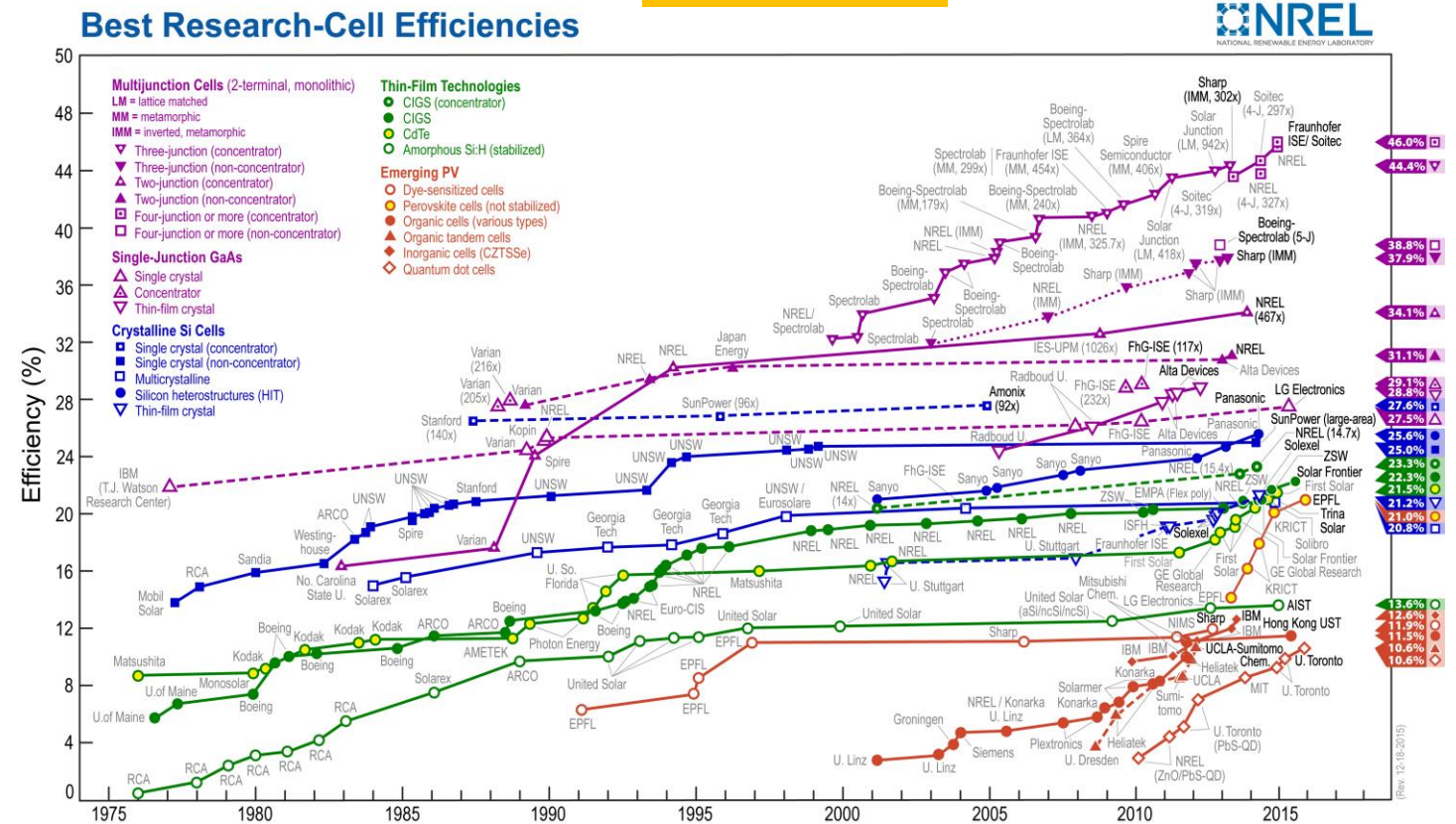
Jusqu'où?



D'où vient la décroissance spectaculaire des coûts de production PV?

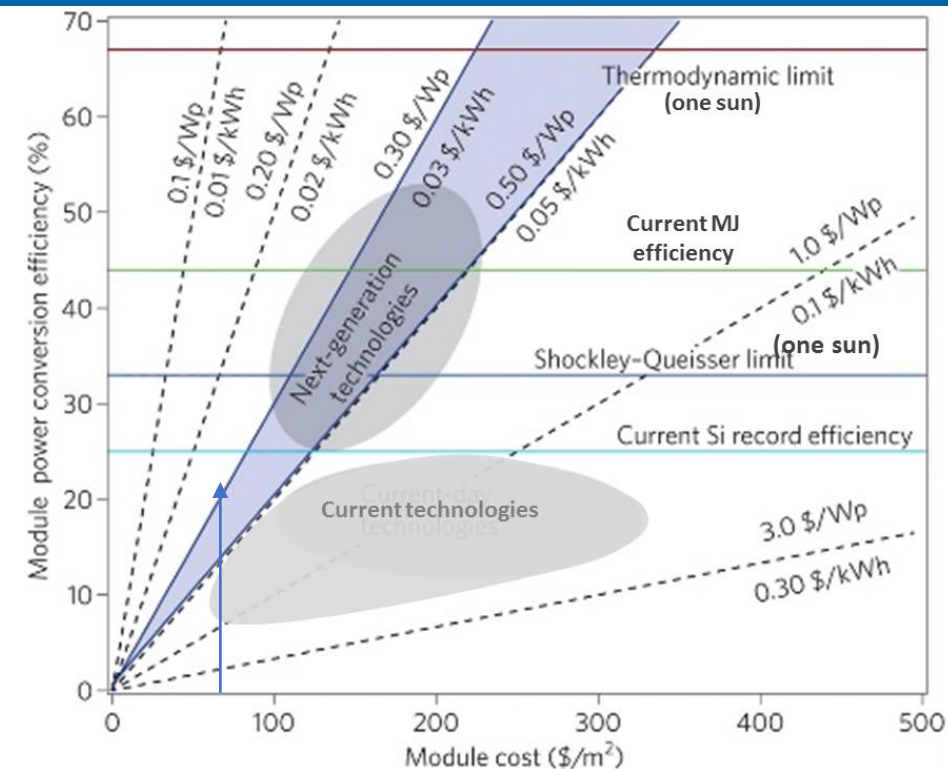
Quelle en est la limite?

+0.6%/yr ↗

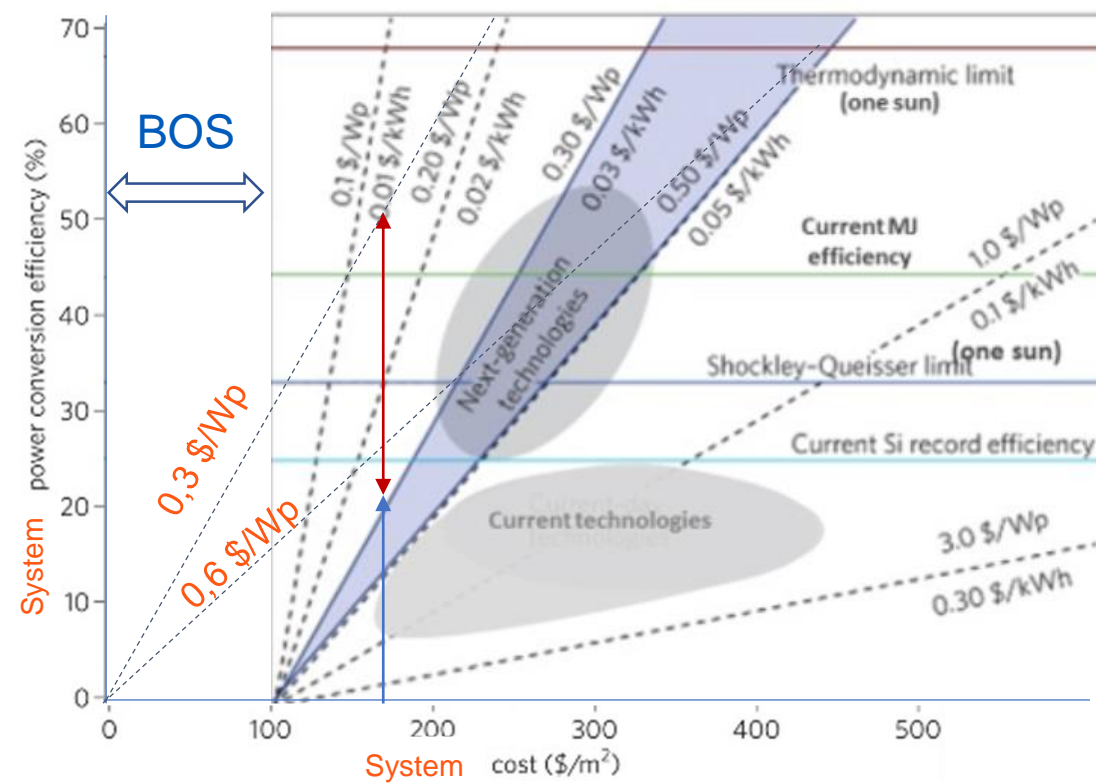


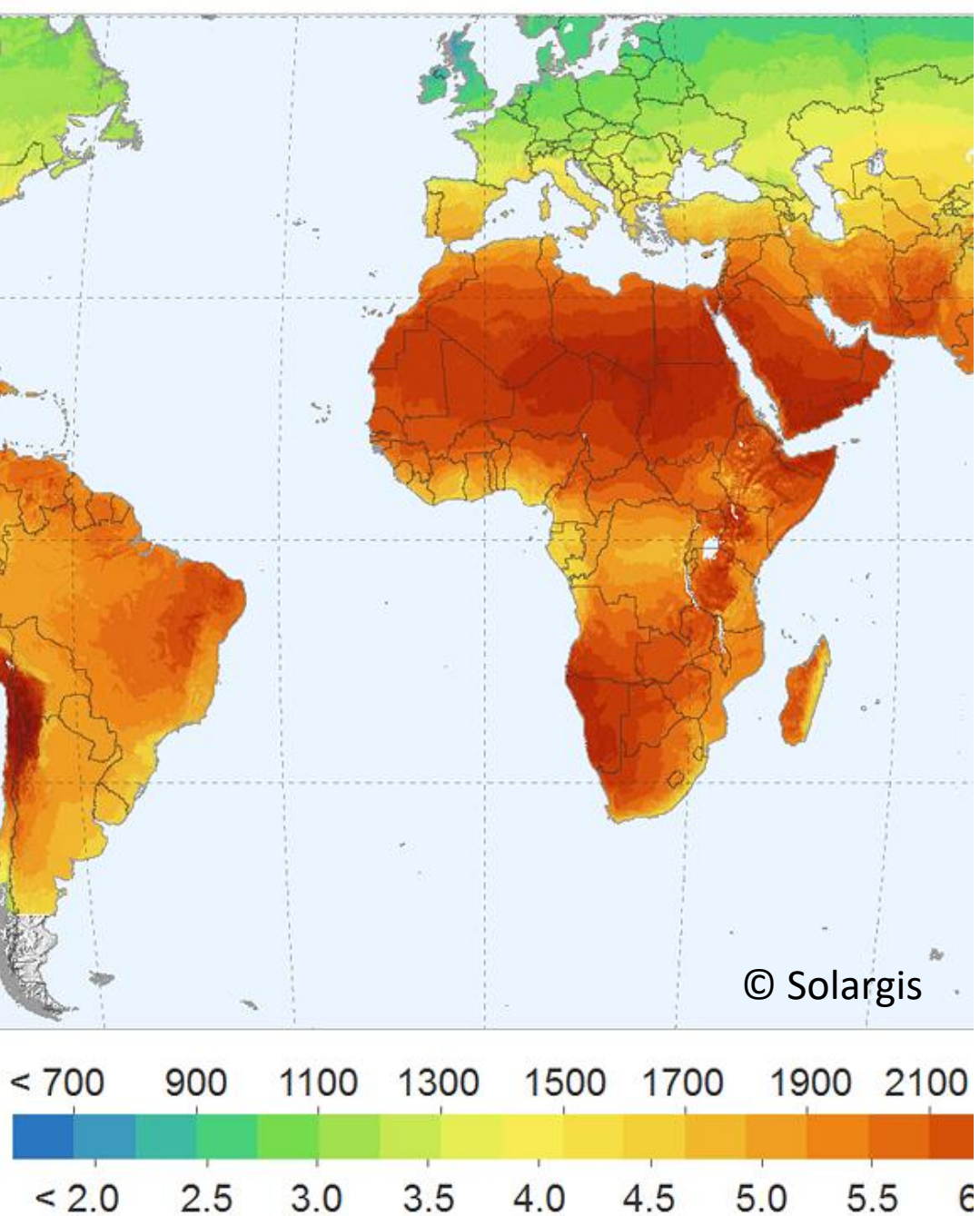
Les défis sur les dispositifs de conversion

- Rendement => Levier coût
 - 20%
- Utilisation des matériaux => Soutenabilité
 - Quelques g/W
- Facteur de charge => Intégration
 - 15% en moyenne en France



Adapted from Beard & Green





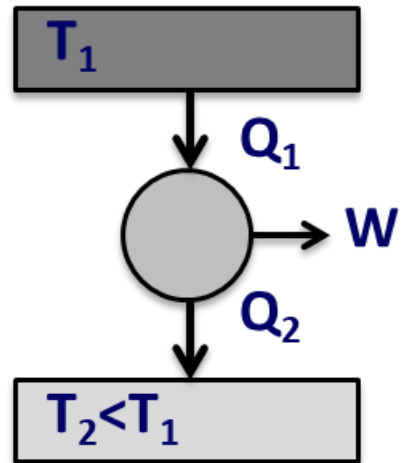
1. Les limites d'efficacité de la conversion Photovoltaïque
2. Questions de soutenabilité



© Cyril FRESILLON / PROMES / CNRS Photothèque

Efficacité

Limites de rendement et description des cellules solaires

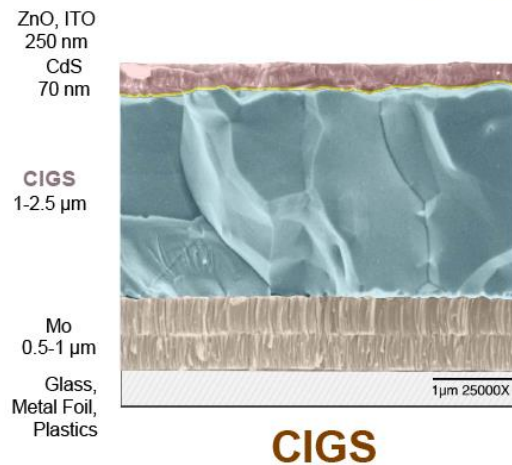
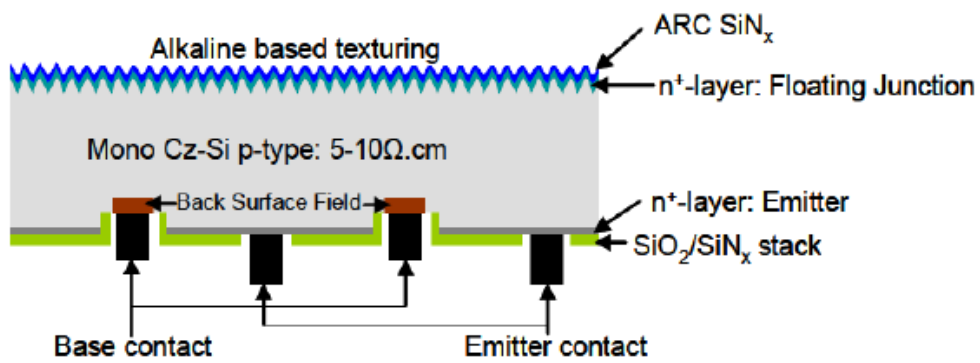
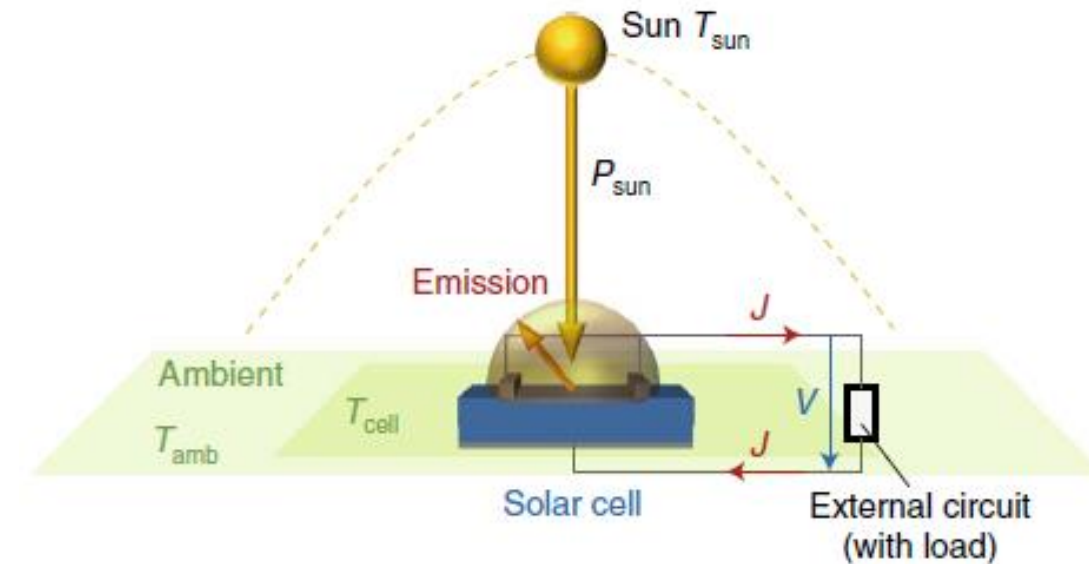


Description de cellules solaires:

Thermodynamique

Optique

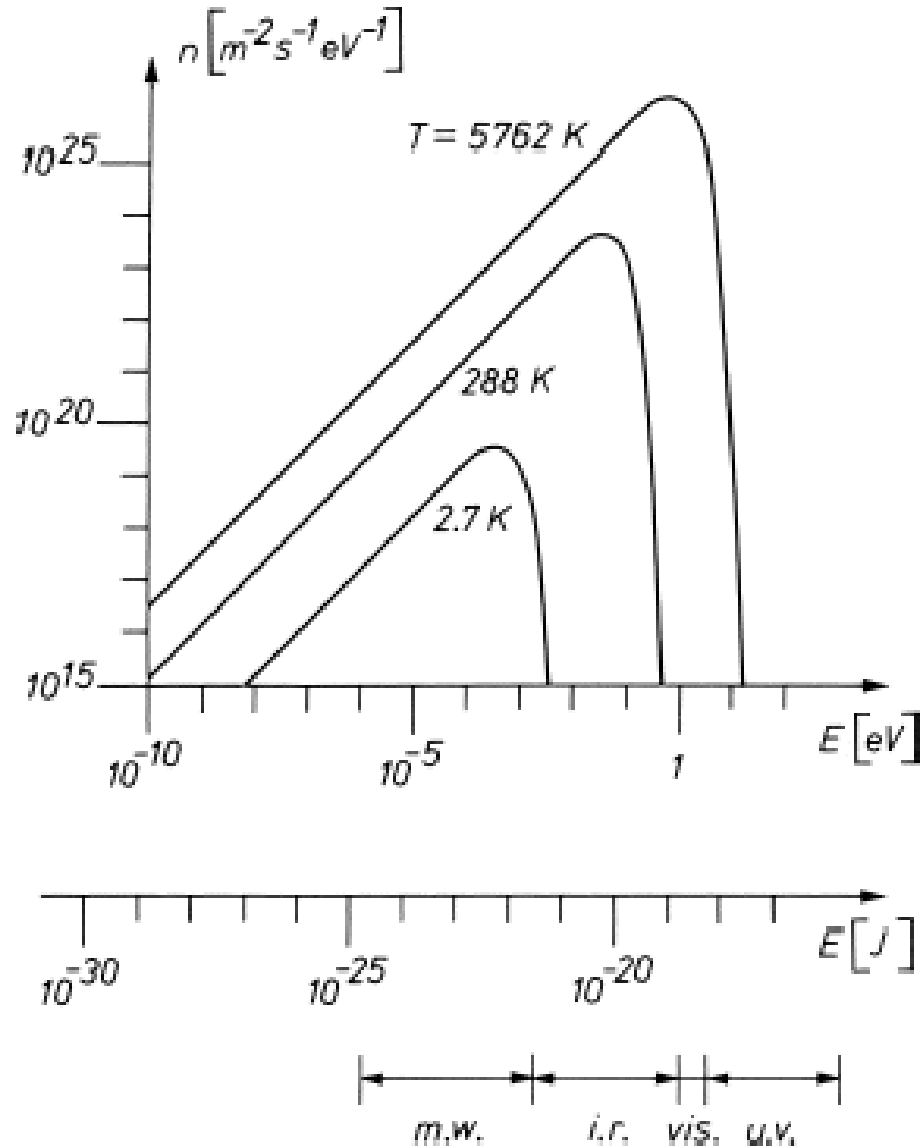
Optoelectronique



$$\text{Carnot: } \left(1 - \frac{T}{T_s}\right) \cong 95\%$$

=> Mais c'est quoi la température du soleil, au fait?

Thermodynamique de la radiation



Kirchhoff, Planck, etc : thermodynamique du rayonnement

Corps noir : Energie et entropie

$$E = \sigma T^4 \quad S = \frac{4}{3} \sigma T^3$$

Limite de concentration solaire et nature géométrique de l'entropie de rayonnement (étendue)*

Carnot corrigé par Landsberg:

(93%)

$$\eta_L = 1 - \frac{4}{3} T_A / T_S + \frac{1}{3} T_A^4 / T_S^4$$

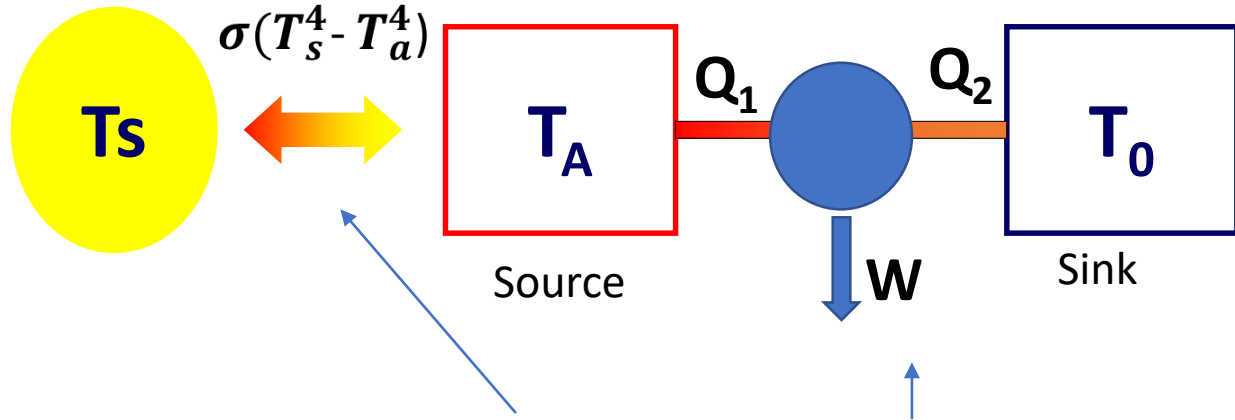
Flux de chaleur tel que $S_{in} = S_{out}$

Travail tel que: $E_{in} = E_{out}$

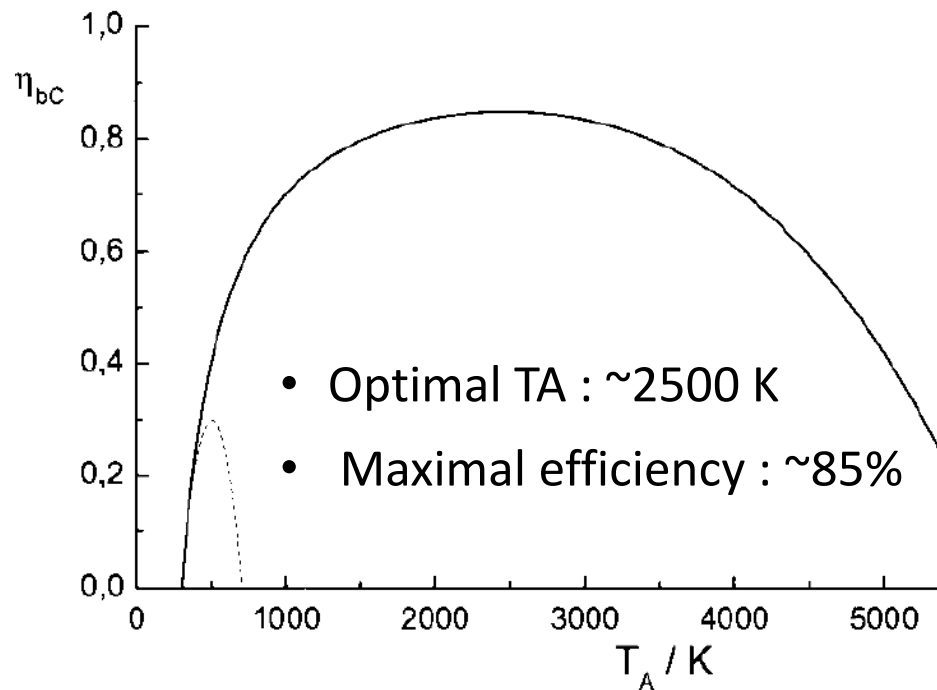
Température de rayonnement généralisée : pour chaque longueur d'onde

D'après « Thermodynamics of Solar Energy Conversion », Alexis De Vos, Wiley-VCH, 1992

* Markvart, T. J. *Opt. A* **10**, 015008 (2008).



$$\eta_{Endo} = \frac{(\sigma(T_s^4 - T_a^4))}{\sigma(T_s^4)} \left(1 - \frac{T_a}{T_s}\right)$$



Carnot, Landsberg: efficacité, sans puissance

Pas de puissance sans flux d'énergie

Pas de flux sans dissipation

⇒ Approche Endoreversible : 85%

Mieux?

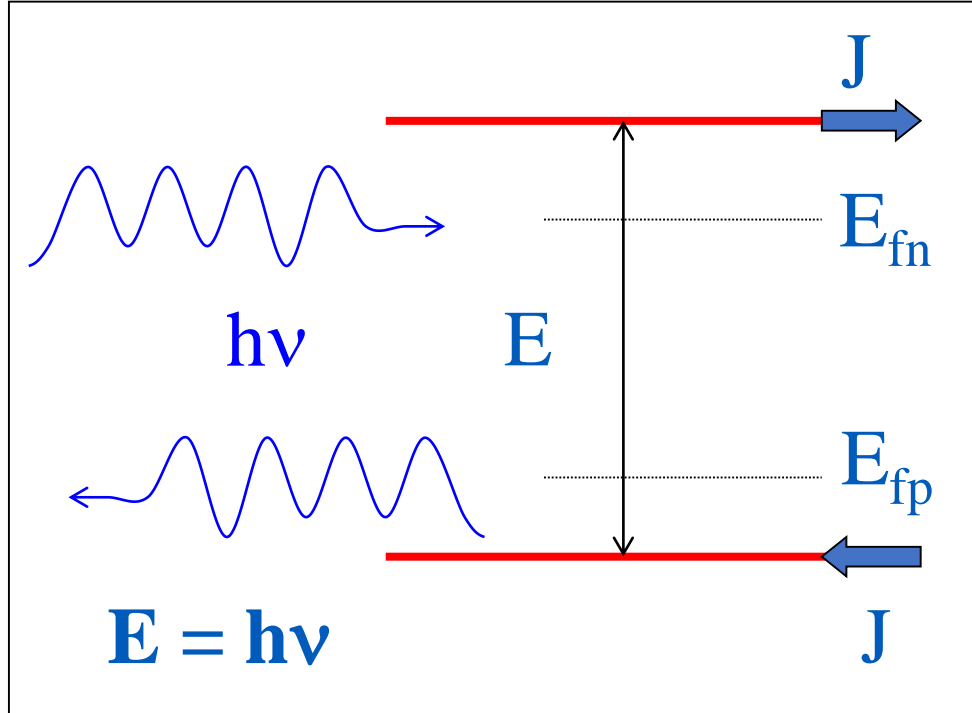
Oui, si la source froide est l'espace intersidéral:

⇒ 99,6%

⇒ Refroidissement radiatif

D'après « *Physics of Solar Cells* », Peter Würfel, Wiley-VCH, 2005

Le système le plus simple : 2 niveaux



$$\mu = qV = E_{fn} - E_{fp}$$

Potentiel chimique des photons

Bilan Détaillé

- Pas de chute ohmique (très hautes mobilités des charges), collecte idéale
- Pas d'absorption parasite
- Limite Radiative

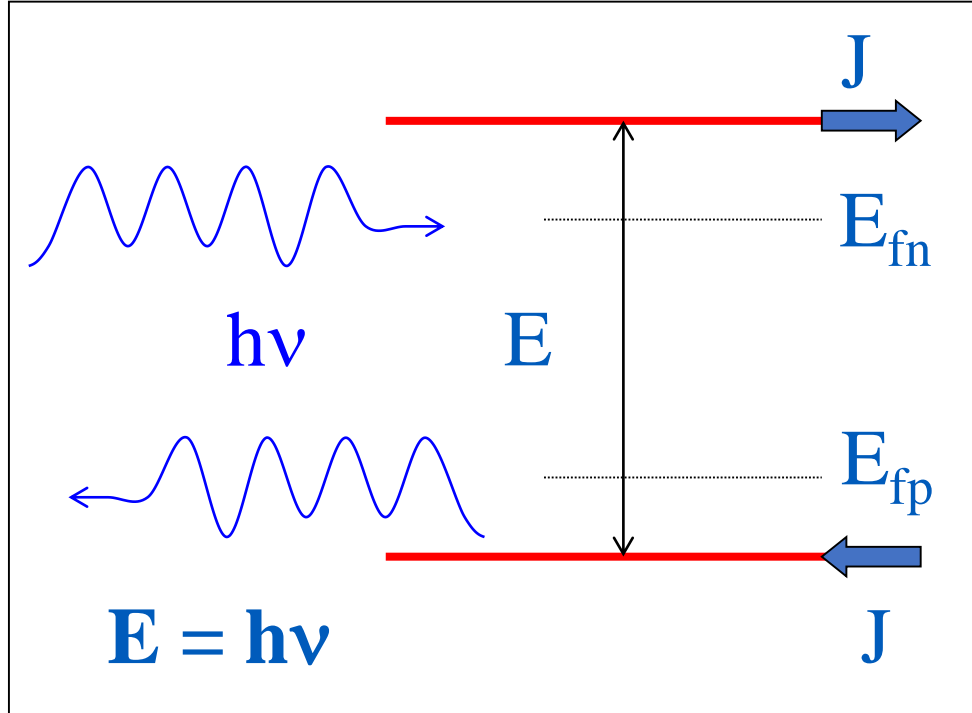
$$J = q \cdot (\Phi_{abs} - \Phi_{em})$$

- Loi de Planck généralisée (microreversibility)

$$\Phi_{em} = A(E) \frac{2\pi E^2}{h^3 c^2} \frac{1}{e^{\left(\frac{E-\mu}{kT}\right)} - 1} = A(E) \frac{2\pi E^2}{h^3 c^2} \cdot f$$

$$\Phi_{abs} = A(E) \frac{2\pi E^2}{h^3 c^2} \bar{f}_{in}(E)$$

Le système le plus simple : 2 niveaux , version Shockley



$$\mu = qV = E_{fn} - E_{fp}$$

- « Photodissociation »

$$h\nu \Leftrightarrow e^- + h^+$$

- $h\nu$: énergie du photon
- Energie libre disponible $\mu = qV = E_{fn} - E_{fp}$

E_f est le niveau de Fermi, ou potentiel électrochimique, ou potentiel redox, ou travail de sortie, ou...

Bilan détaillé:

$$J = q \cdot (\phi_{abs} - \phi_{em})$$

$$\phi_{em} = B \cdot n \cdot p \approx B n_i^2 \cdot \exp\left(\frac{qV}{kT}\right)$$

L'équation de Shockley de la diode est une loi d'action de masse

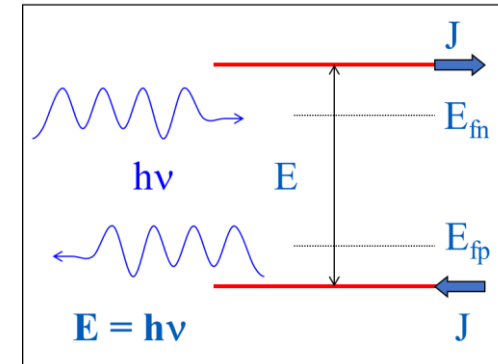
Rendement optimal de conversion d'une longueur d'onde

$$\eta = \frac{P}{P_{inc}}$$

$$P = J \cdot V = \mu \cdot (\Phi_{abs} - \Phi_{em}(\mu))$$

Au point de puissance Maximale

$$dP=0 \text{ et: } \eta = J_{mp} \cdot V_{mp} / P_{inc} = J_{mp} \cdot q V_{mp} / (E \cdot I_{ph})$$



Pour un système à la limite radiative

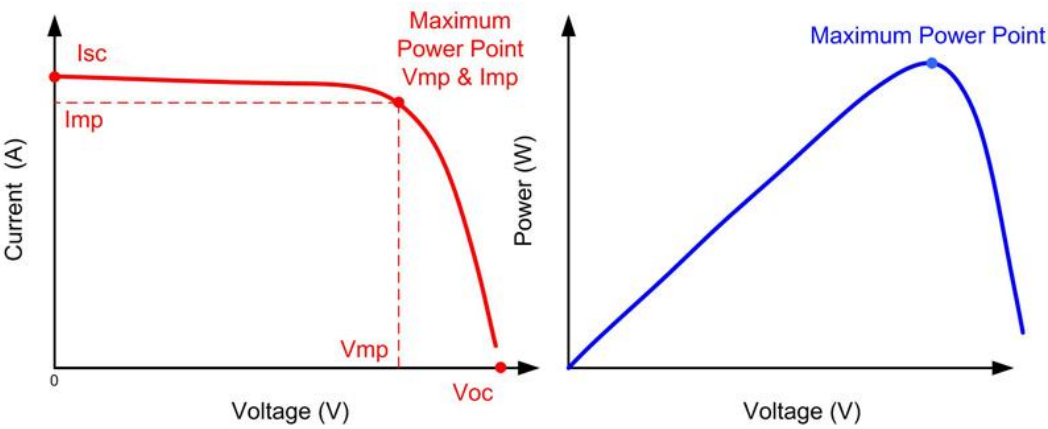
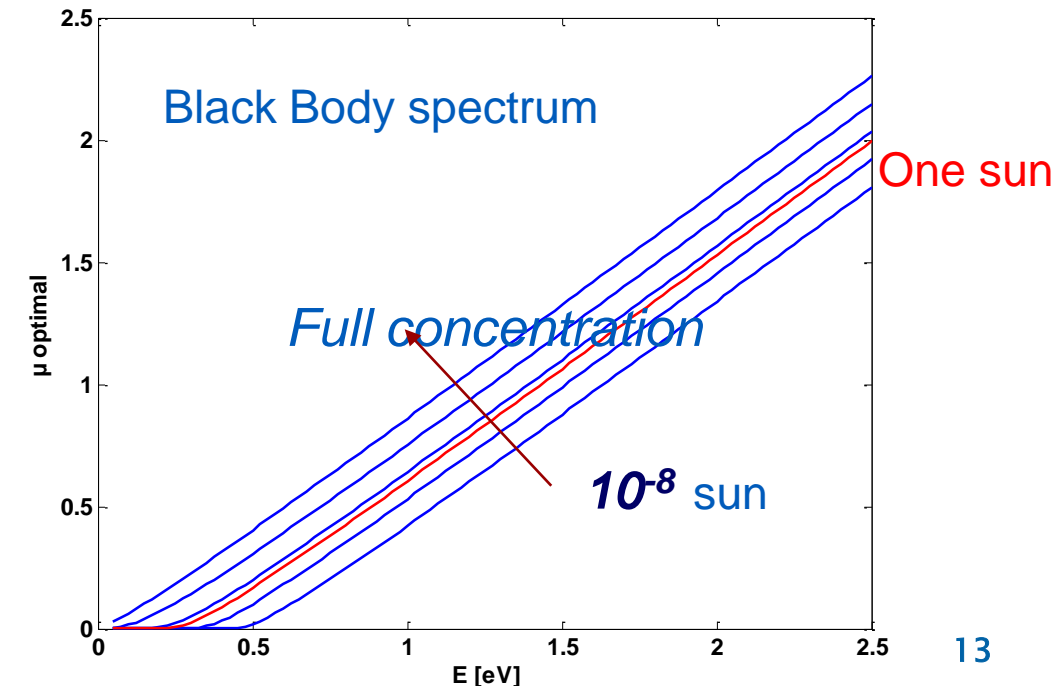
- Potentiel chimique de photon et tension optimaux
- Distribution de photon optimale

$$\mu_M = q \cdot V_m$$

$$f_M = \frac{1}{\exp\left(\frac{E - \mu_M}{kT}\right) - 1}$$

$$\bar{f}_{inc} = f_M \cdot \left[1 + (1 + f_M) \cdot \left(\frac{E}{kT} - \ln\left(\frac{1 + f_M}{f_M}\right) \right) \right]$$

$$I_m = q \frac{2\pi E^2}{h^3 c^2} (\bar{f}_{inc} - f_M) = I_{ph} \left(1 - \frac{f_M}{\bar{f}_{inc}} \right)$$



Open circuit

$$\mu_{oc} = q \cdot V_{oc} = E_g \cdot (1 - T/T_s)$$

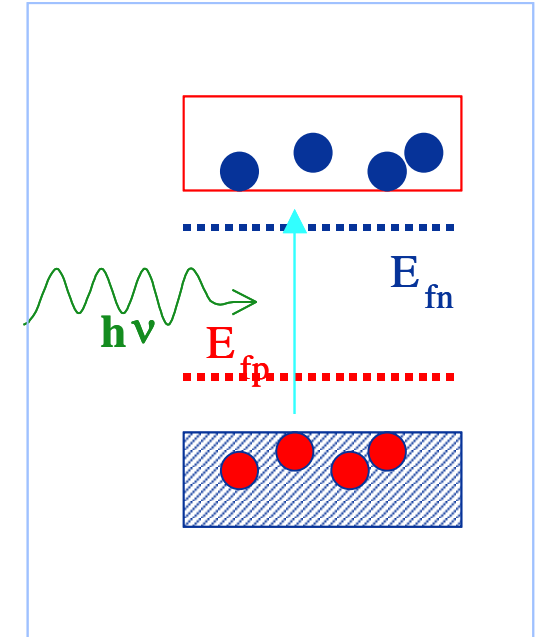
(Mind Carnot factor)

Du système à 2 niveau aux semiconducteurs

- Mêmes hypothèses
- 2 Bandes plutôt que 2 niveaux+ chaque bande est en quasi-équilibre

$$dn(E) = \frac{dN(E)}{dV} = D(E) \cdot f(E) \cdot dE$$

$$n = \int D(E) \cdot f(E) dE$$

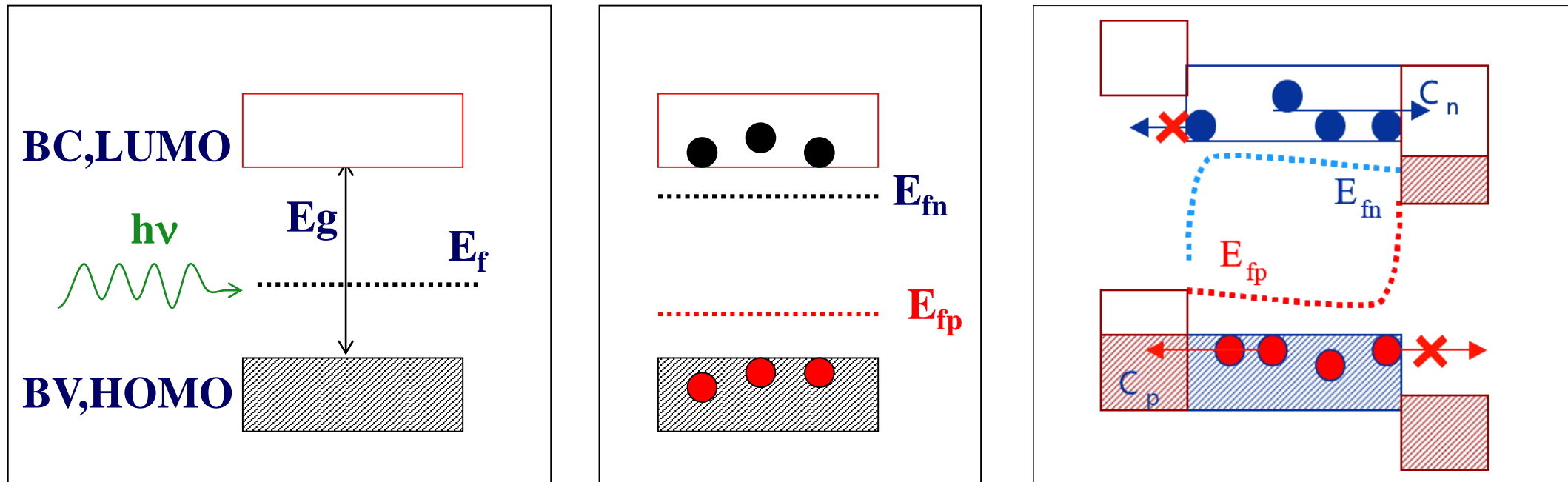
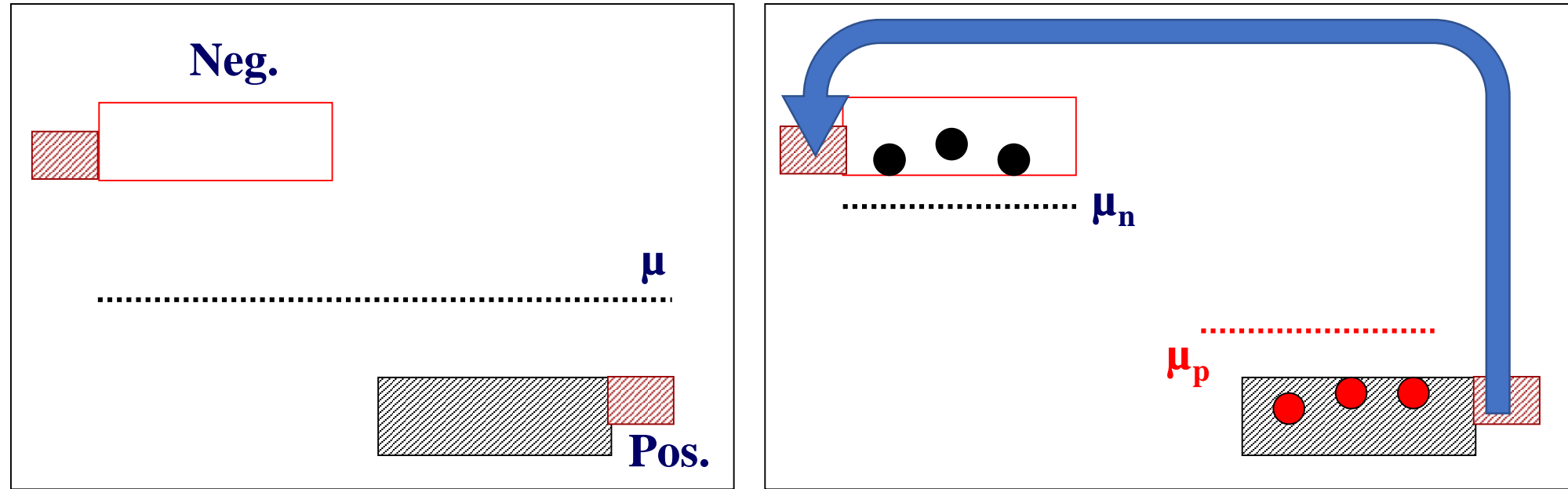


	Photons	Electrons
Extractible free energy per particle	$\mu = E_{fn} - E_{fp}$	$qV = E_{fn}^n - E_{fp}^p$
Current	$\Phi_{abs} - \Phi_{em}$	$I = q \cdot (\Phi_{abs} - \Phi_{em})$
Power	$P_\gamma = \mu \cdot (\Phi_{abs} - \Phi_{em}(\mu))$	$P = I \cdot V$

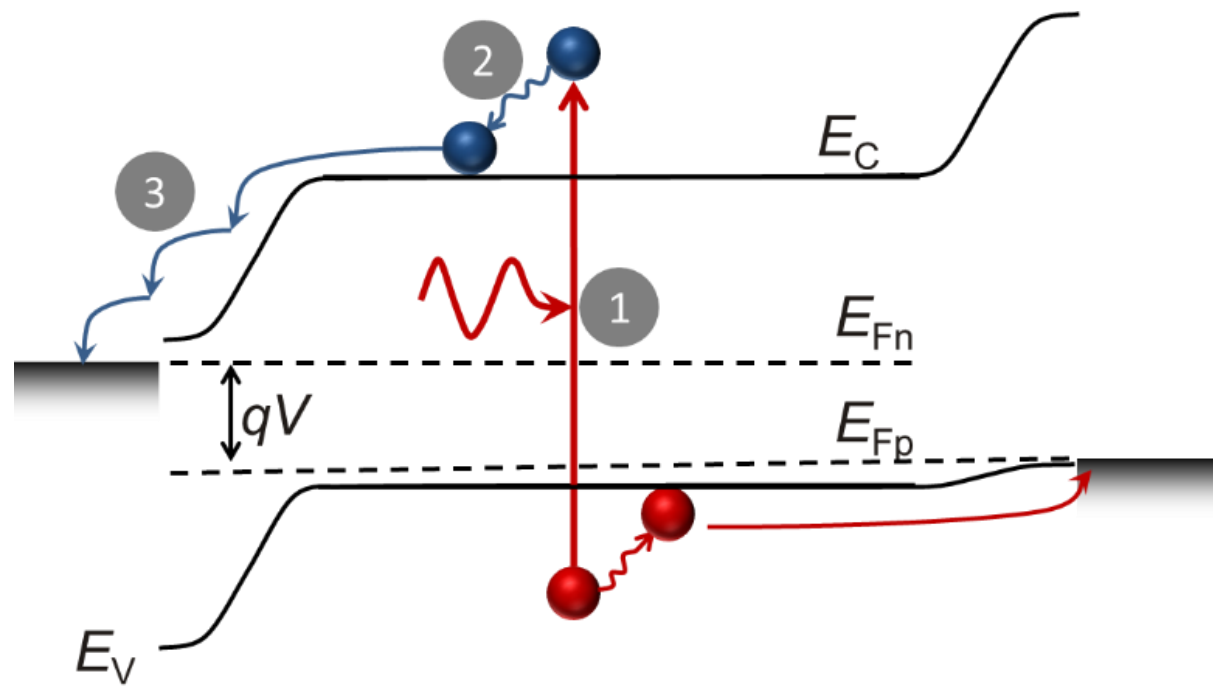
$$\Phi_{em} = \int \dot{N}_{em}(E) \cdot dE \quad \Phi_{abs} = \int A(E) \cdot \dot{N}_{inc}(E) \cdot dE$$

$$\dot{N}_{em}(E) = \frac{2\pi}{h^3 c^2} A(E) \frac{E^2}{e^{(E-\mu)kT} - 1}$$

Une pile solaire est elle une batterie?

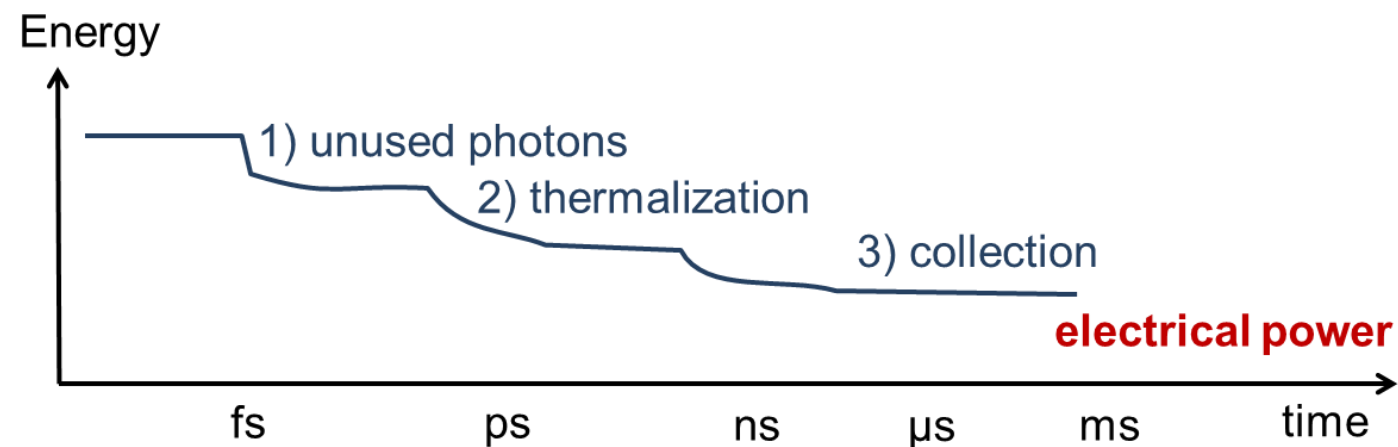


Types de pertes

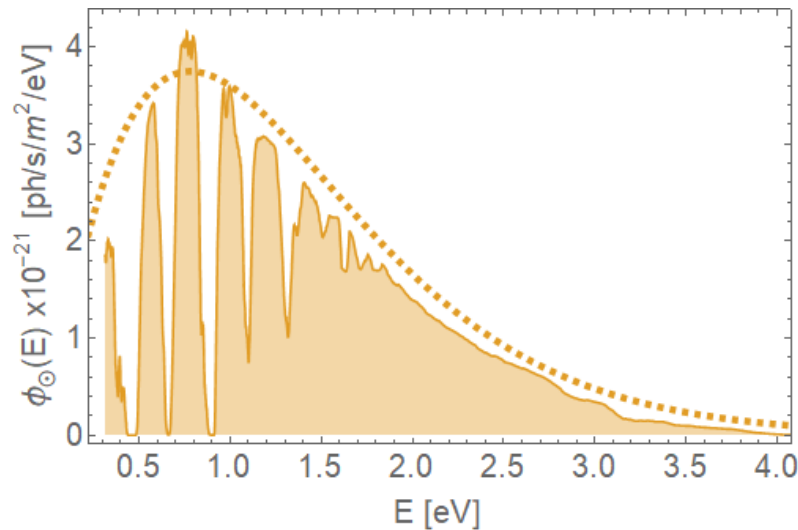
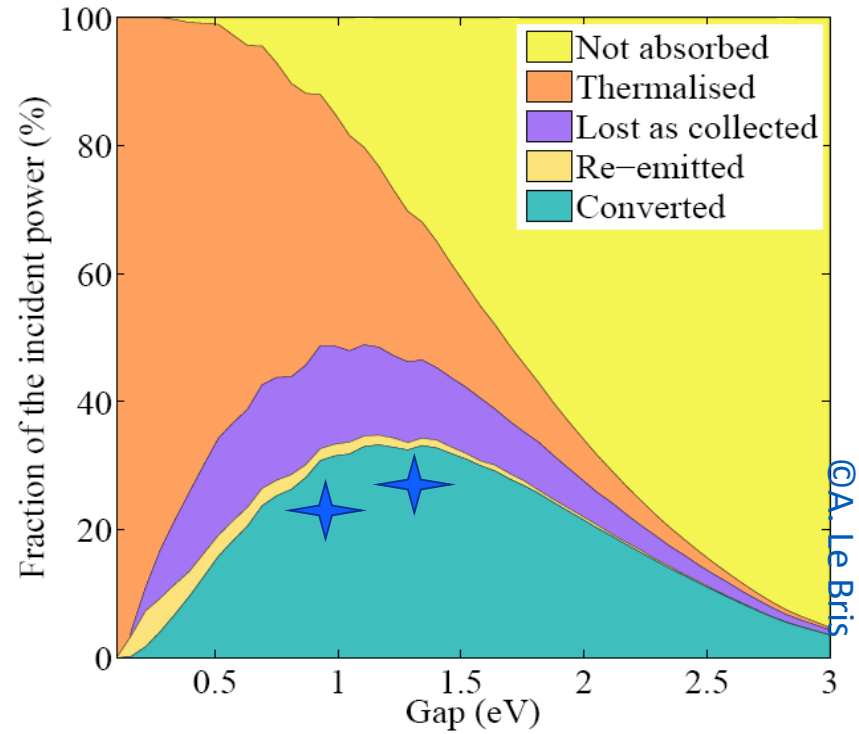


Plusieurs mécanismes de pertes

Compétition entre relaxation par le circuit extérieur et relaxation interne



Modèle Shockley-Queisser



- Modèle de référence (Shockley, W. & Queisser, H. J. *J. Appl. Phys.* **32**, 510–519 (1961))
- Idealisation basée sur des hypothèses
 - $(1 \text{ hv} \Leftrightarrow 1 \text{ eh pair})$ si et seulement si $h\nu > E_g$
 - Marche abrupte d'absorption (transparence/absorption totale)
 - Limite radiative
 - Stoechiometrie (1 seul photon correspond à une seule paire)
 - Fonctionnement Isotherme
 - Collecte idéale aux contacts
- Only optical properties enter
- 3x1/3 rule

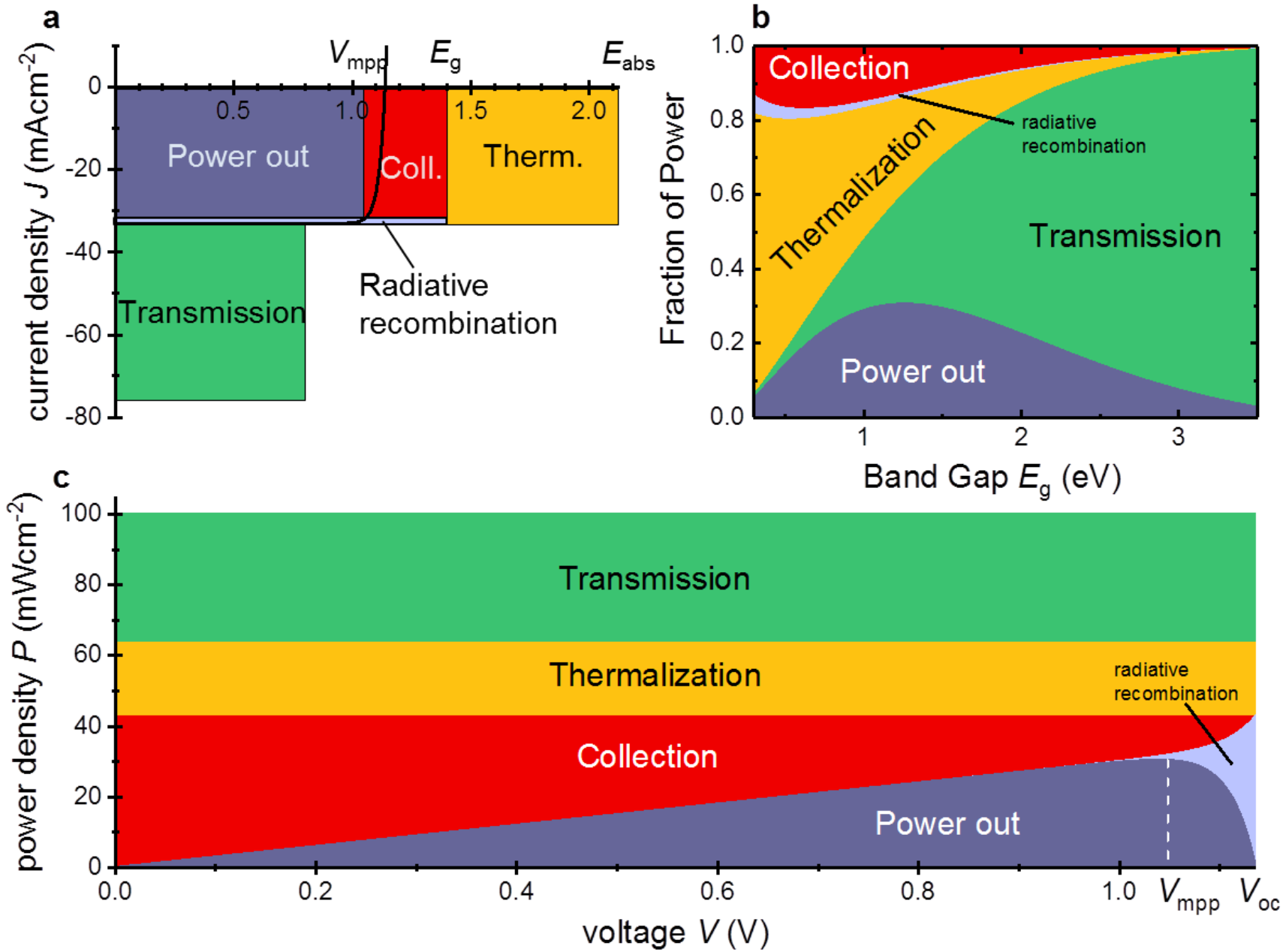
Fonctionnement accessible par des techniques de luminescence

Guide for the perplexed to the Shockley-Queisser model for solar cells

Jean-Francois Guillemoles , Thomas Kirchartz , David Cahen  & Uwe Rau 

Nature Photonics **13**, 501–505 (2019) | [Download Citation](#) ↓

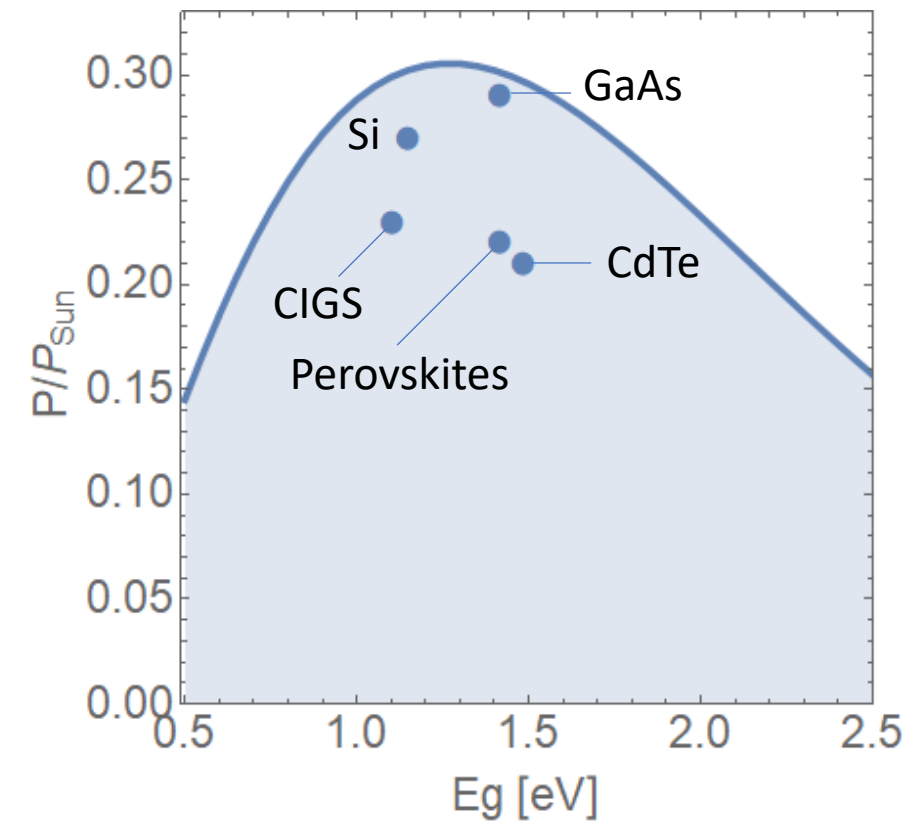
Pertes II

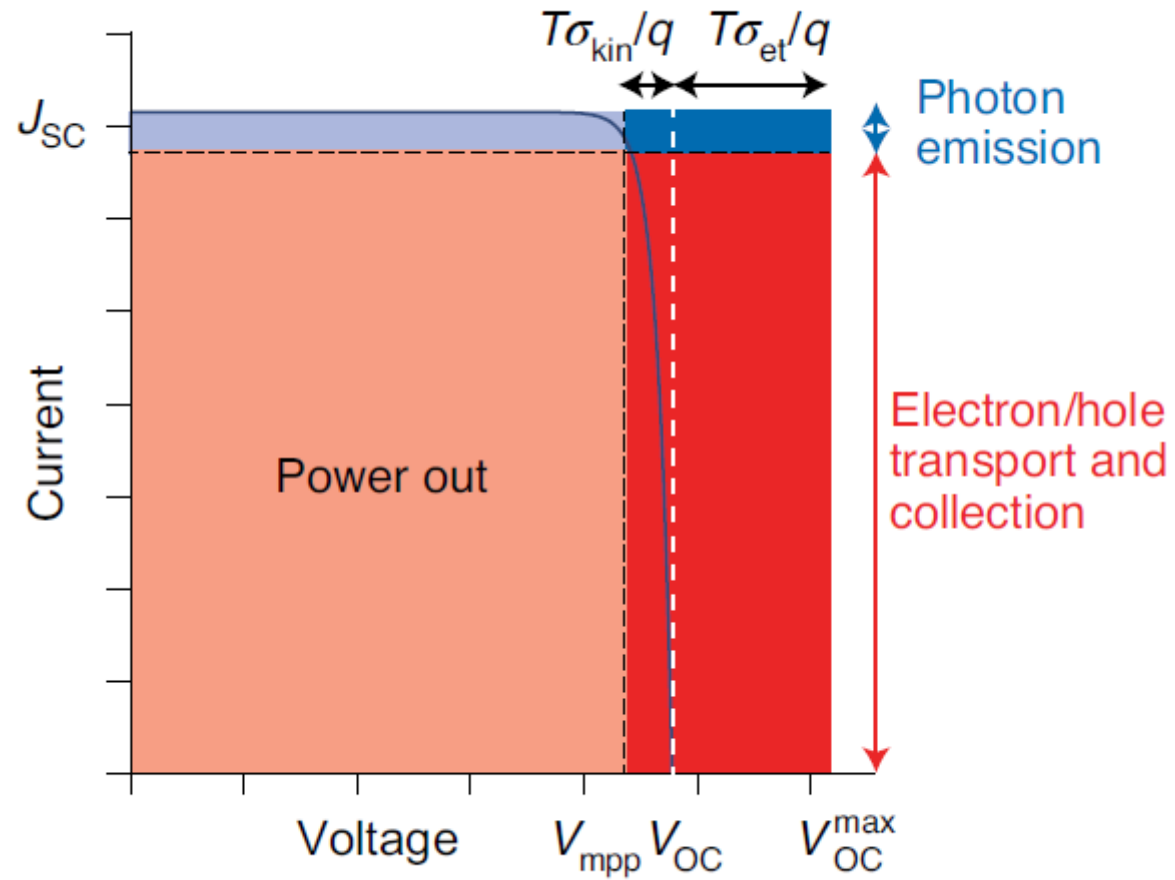


(a) At MPP on the IV; (b) versus band gap (at MPP); (c) as a function of applied voltage.

La classification des pertes dépends

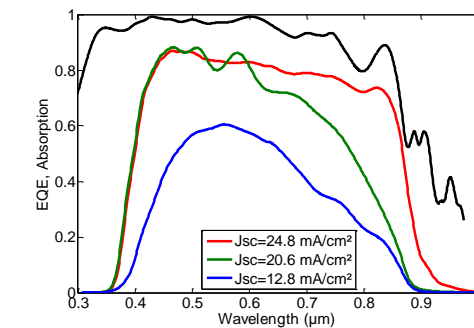
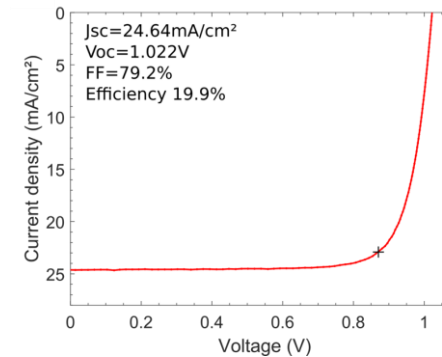
- i) Du point de fonctionnement
- ii) Du gap du matériau absorbant



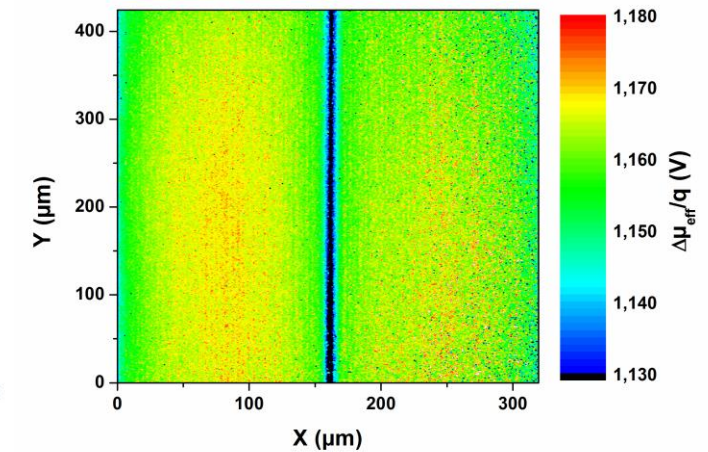
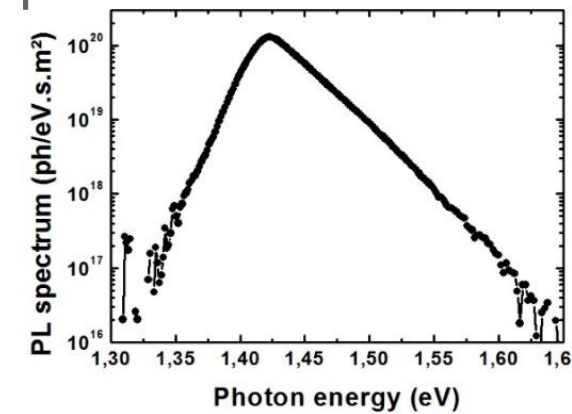


Deux représentations possibles et complémentaires:

- Les Fermions (électrons et « trous »): vision globale de la conversion, accès direct aux paramètres cinétiques et transport



- Les bosons (à la limite radiative, photons seulement): vision locale de la conversion, accès direct aux paramètres thermodynamiques



$$\Phi_{PL}(E) = \frac{A(E)E^2}{4\pi^2 \hbar^3 c_0^2} \frac{1}{\exp\left(\frac{E - \Delta\mu}{kT}\right) - 1}$$

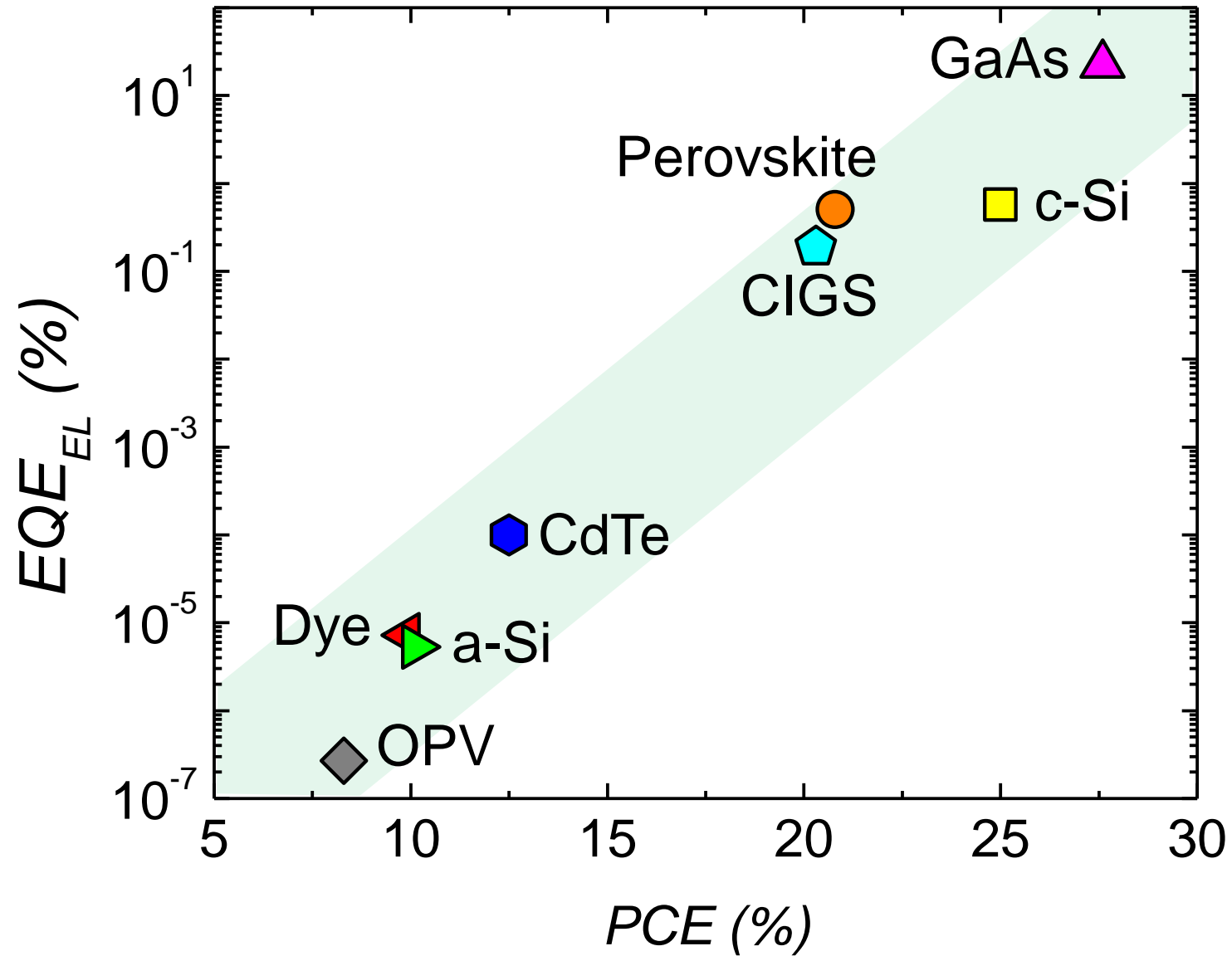
Lien bosons-fermions : $\mu = E_{fn} - E_{fp}$

Guillemoles, J.F. "Fundamental Physical Limits to Photovoltaic Conversion." Wiley & Sons, 2014.

Guillemoles, J.F., Kirchartz, T., Cahen, D. *et al.* *Nat. Photonics* **15**, 165–166 (2021).

A. Delamarre, L. Lombez, JF Guillemoles, "Contactless mapping of saturation currents in solar cells by photoluminescence", *Applied Physics Letters*, **100**, (2012) 131108

Rendement radiatif et performance : au-delà de la limite radiative

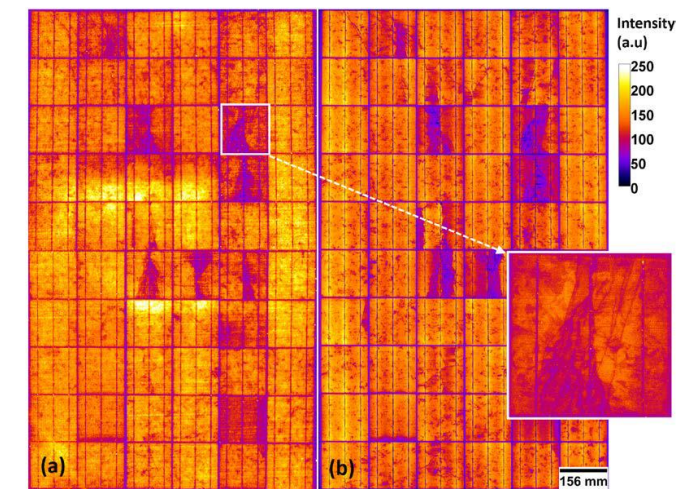


From M. Sessolo, U. Valencia;

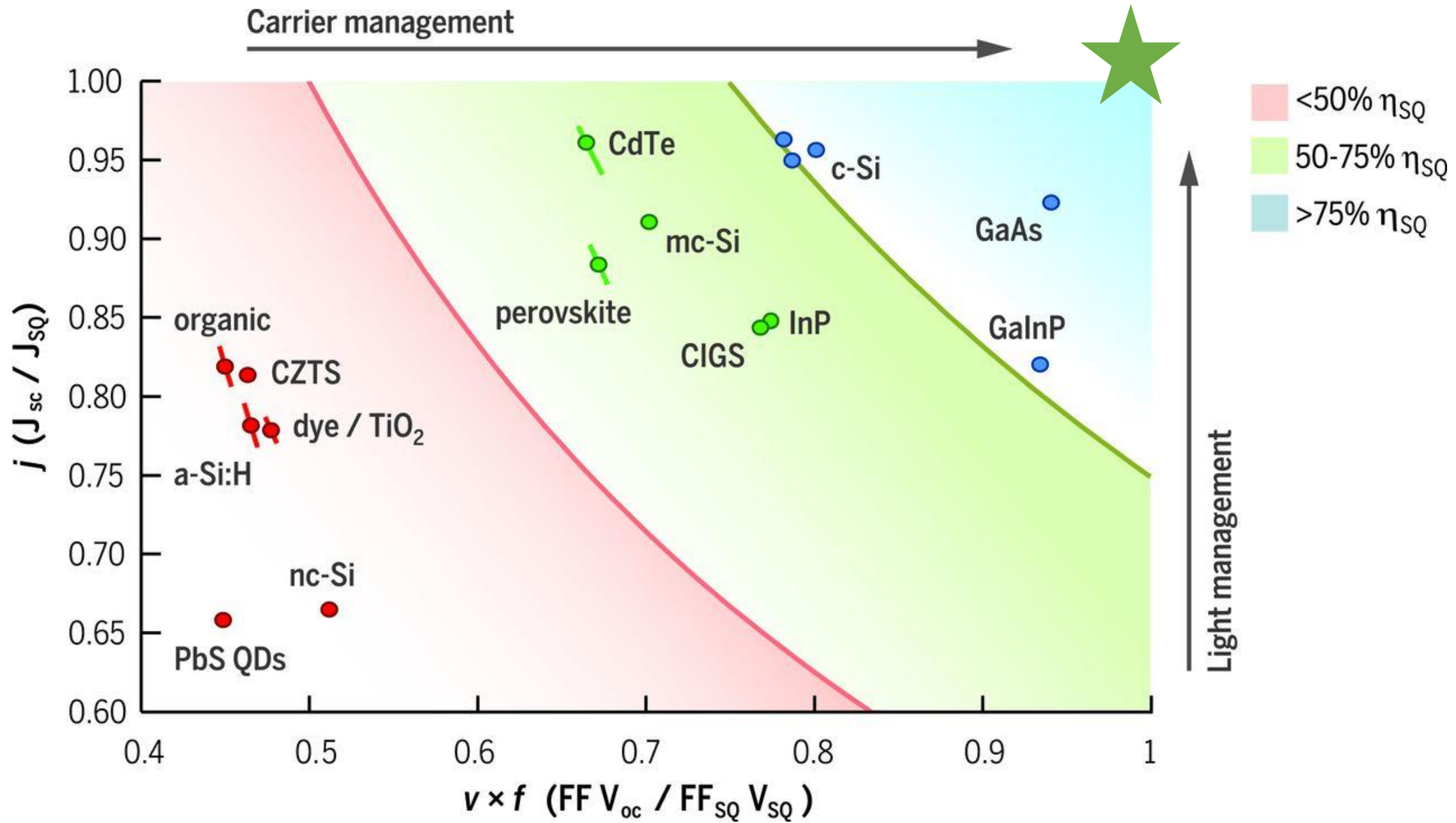
Recombinaisons non radiatives: facteur multiplicatif sur les pertes

Conversion Photon-electron : corrélée à l'émission de lumière

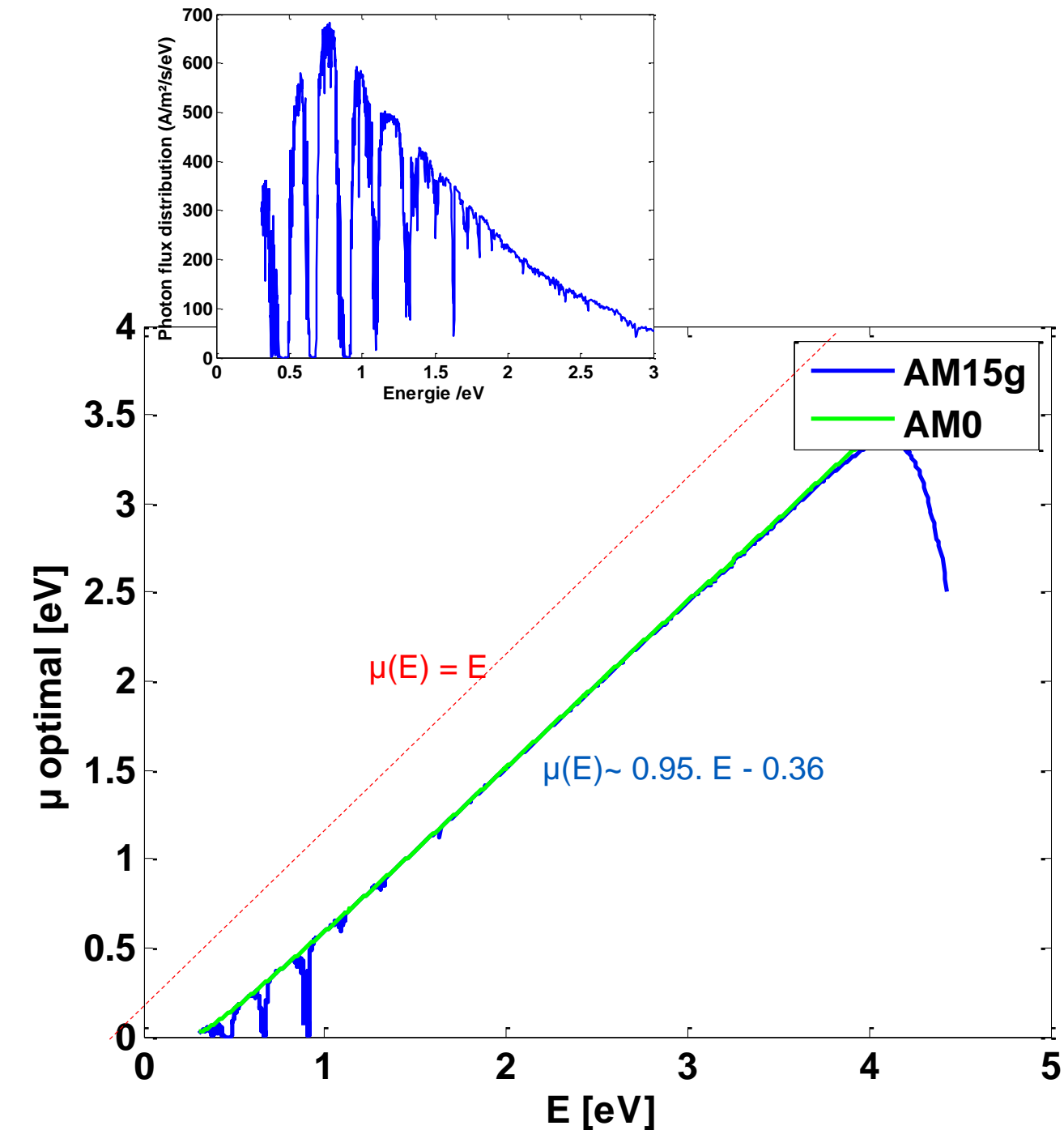
=> Ouvre la voie à des approches de caractérisation de cellules solaires



Indoor EL image of a c-Si module.
Trupke et al. PIP, UNSW 2018



Closing in on limits with single junctions



L'énergie libre disponible dépend de

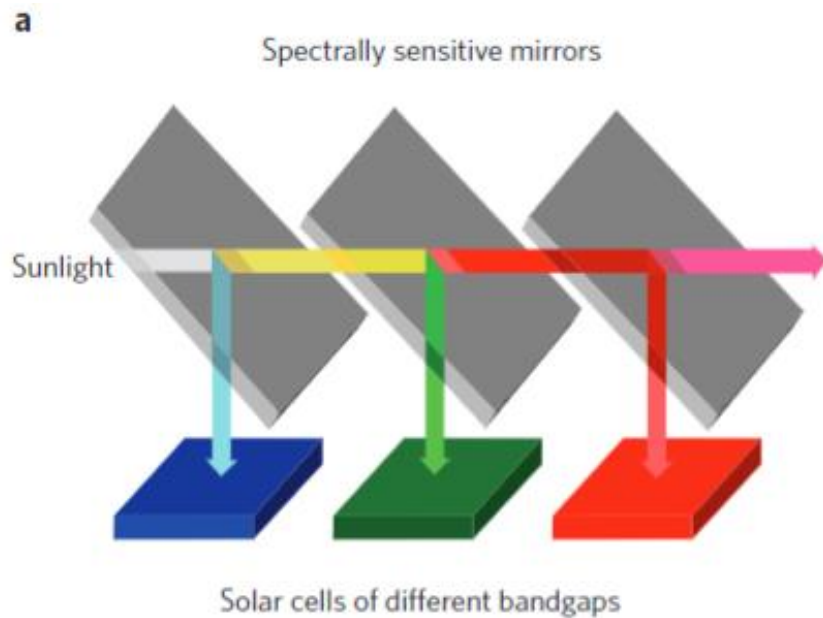
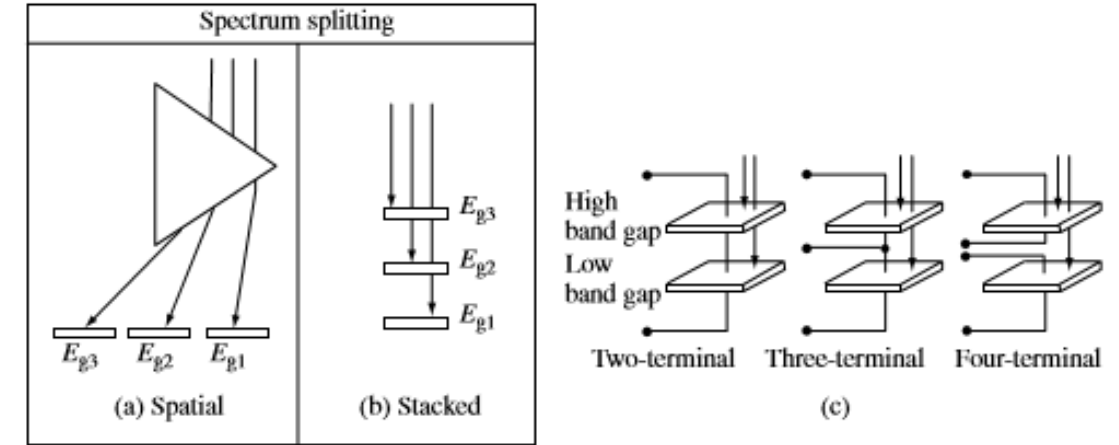
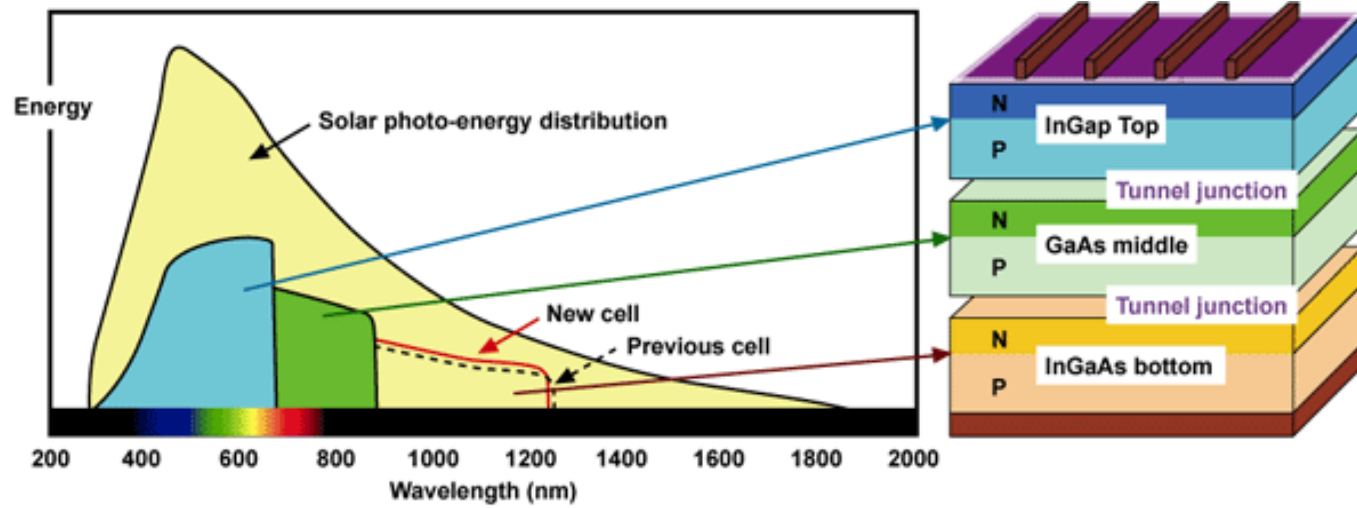
- L'énergie du photon converti
- De la température des électrons produits
- De l'intensité du flux de photons

$\mu_M(E)/E \sim 0.7$ en moyenne pour AM 1.5

⇒ Rendement optimal chromatique **67,8%**

⇒ **87%** sous concentration

Multijonctions : un convertisseur chromatique



⇒ Mieux couvrir le spectre solaire par rapport à la simple jonction

⇒ Mieux tirer parti de chaque longueur d'onde

Multijonctions : Réalisations et état de l'art

Junctions	1	2	3	4	5	6
AM 1.5	29,1%	32.8 %	37.9%		38.8%	
Max eff	29.3% x50	35.6% x40	44.4% x300	46.0% x500		47,1% (x143)







nature
energy

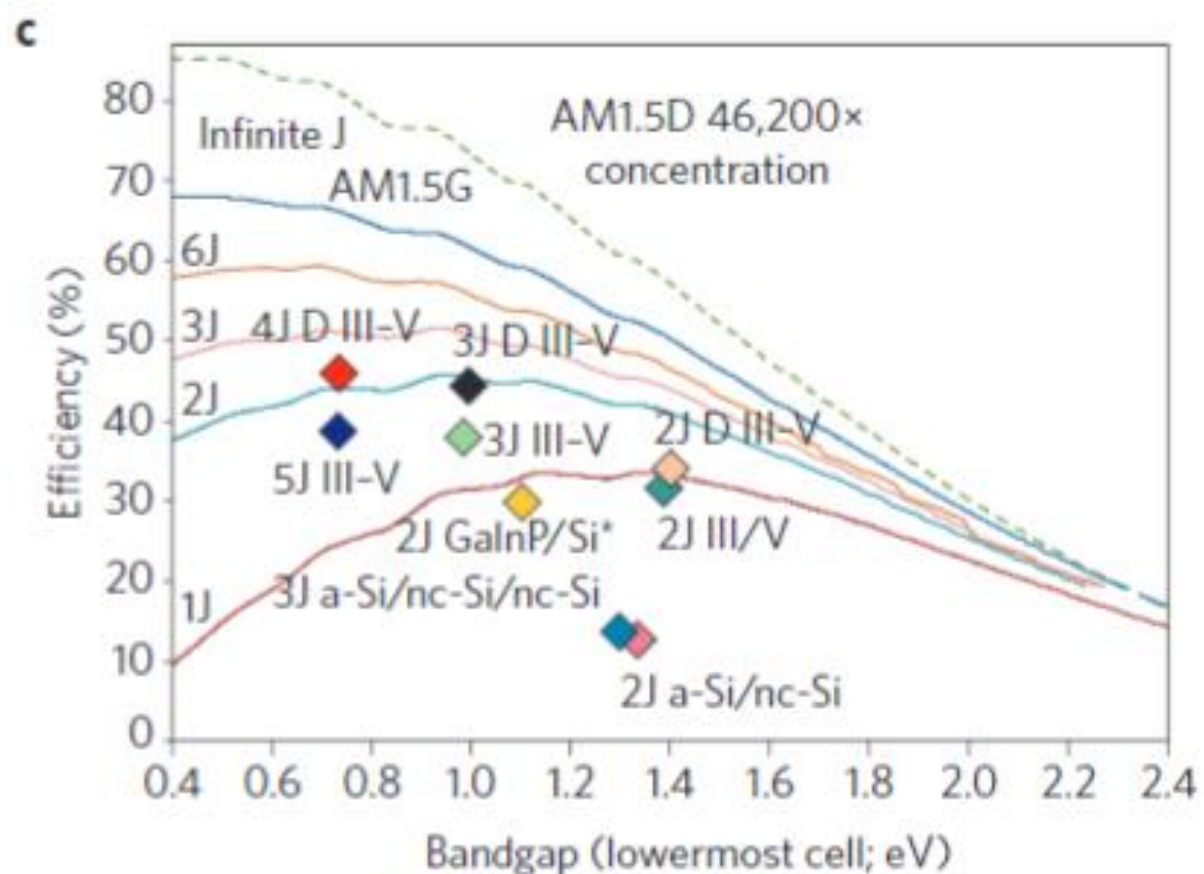
ARTICLES

<https://doi.org/10.1038/s41560-020-0598-5>

Check for updates

Six-junction III-V solar cells with 47.1% conversion efficiency under 143 Suns concentration

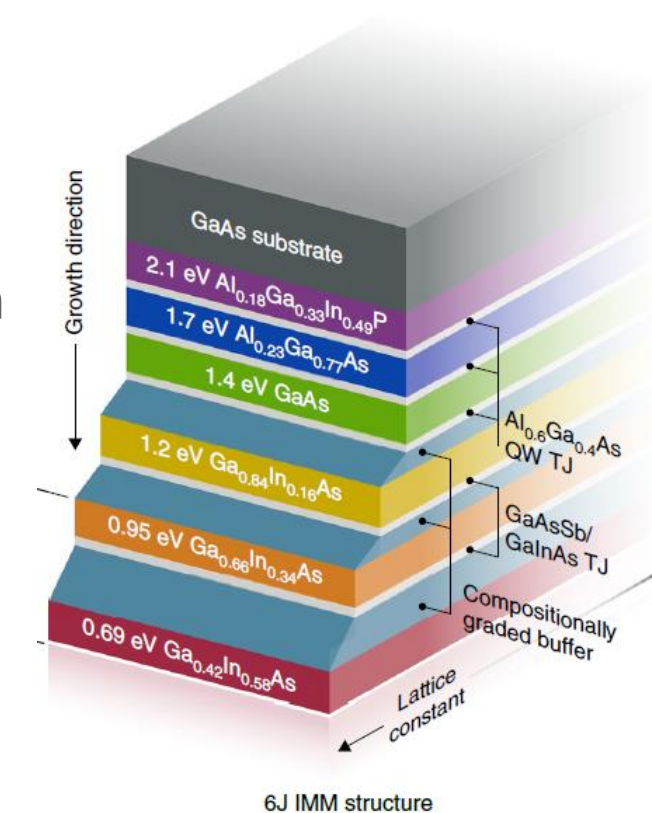
John F. Geisz , Ryan M. France , Kevin L. Schulte , Myles A. Steiner , Andrew G. Norman , Harvey L. Guthrey , Matthew R. Young, Tao Song and Thomas Moriarty



Still far from optimum

Significant gain from concentration

- III-V
- Si-Based
- Thin film



Multijunctions: limitations

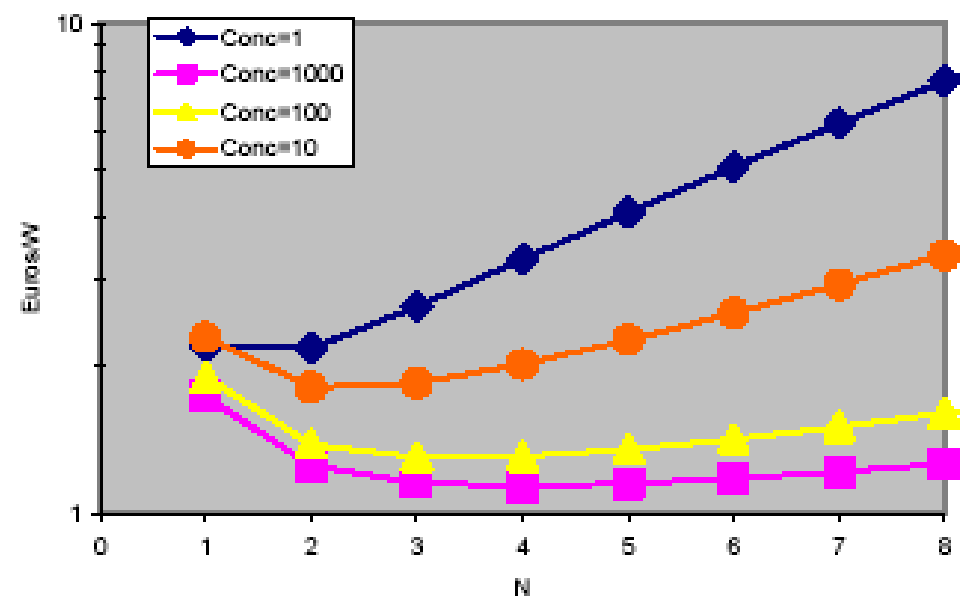
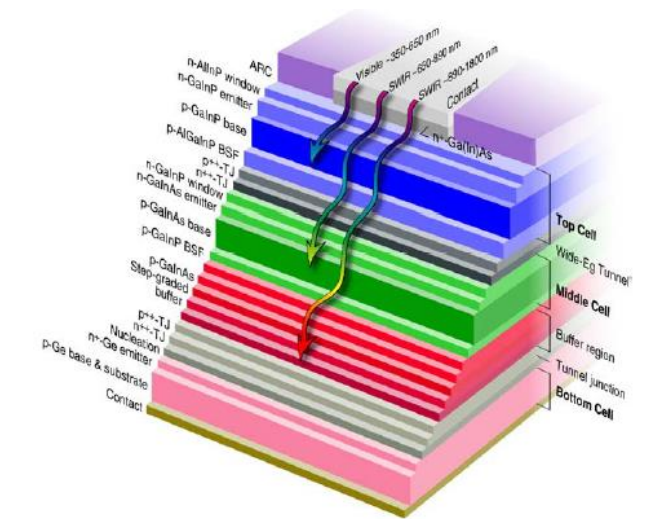
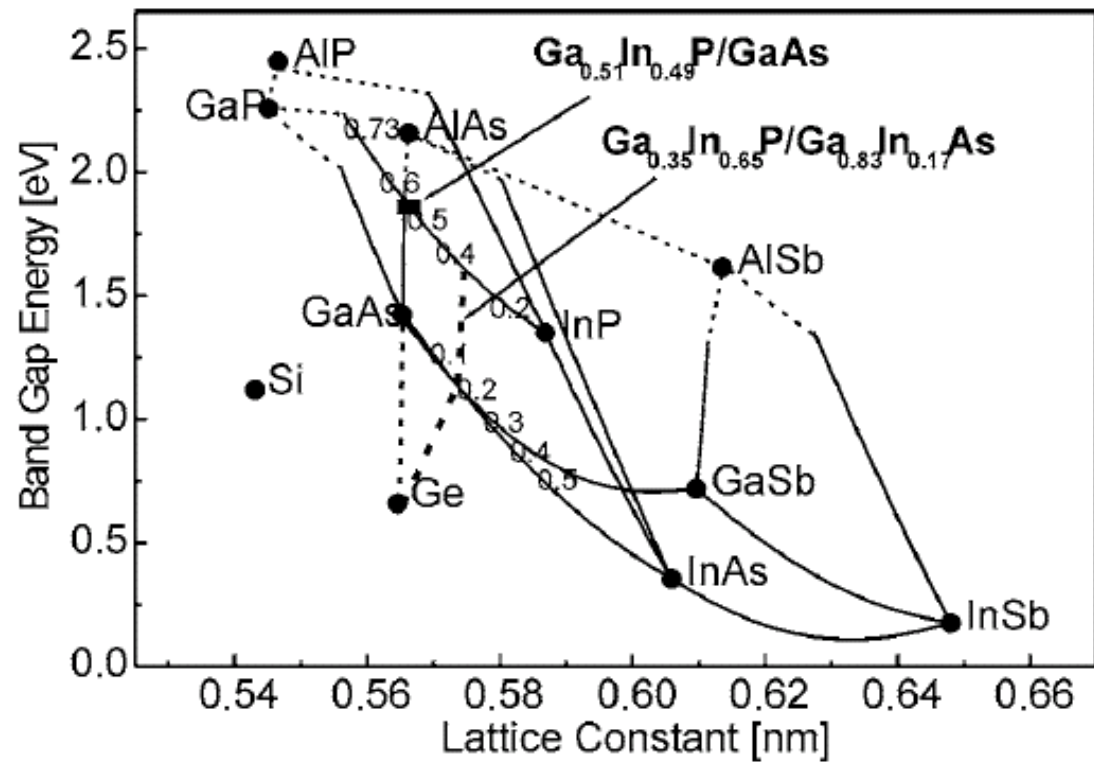
- Constrained efficiency
 - ✓ lattice matching ($\ll 0.1\%$)
 - ✓ current matching

- Cost of substrate

- Decreasing marginal gain

$$\eta(N) = \frac{\eta^\infty}{1 + a/N}$$

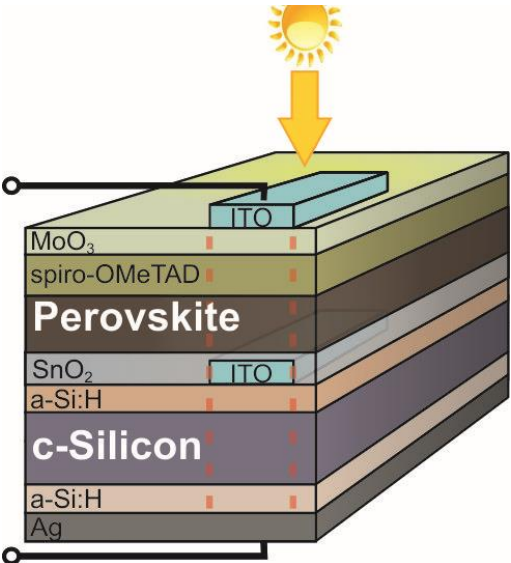
$\eta^\infty : 68\%$ (AM1.5)
 à 86.8% (x46200)
 $a \sim 1$



Complexes

- Production yield losses
- Optical losses (Transparency)
- Electrical losses (Tunnel junctions)
- Mitigated success for a-Si

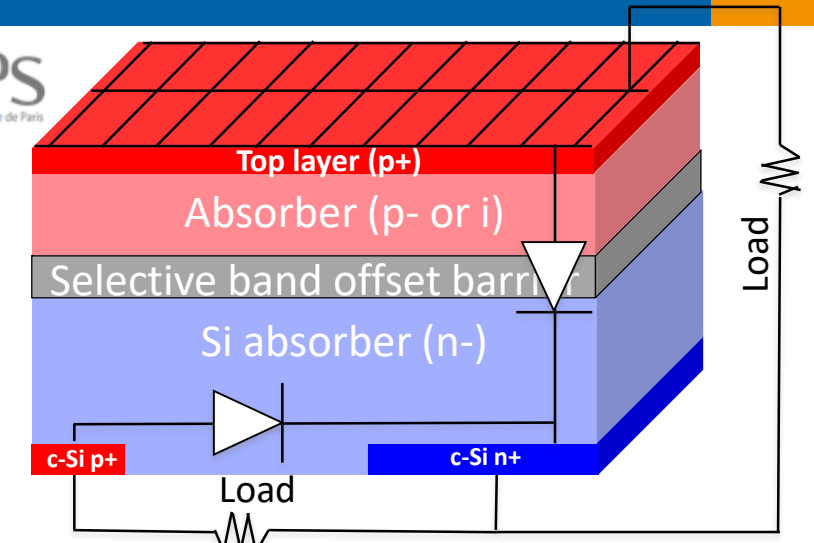
Nouvelles approches des Tandems



S. Albrecht et al., *Energy Envir. Science*, 9 (2016)

29,5% (2020, Oxford PV)

Tandems couches minces polycristallines

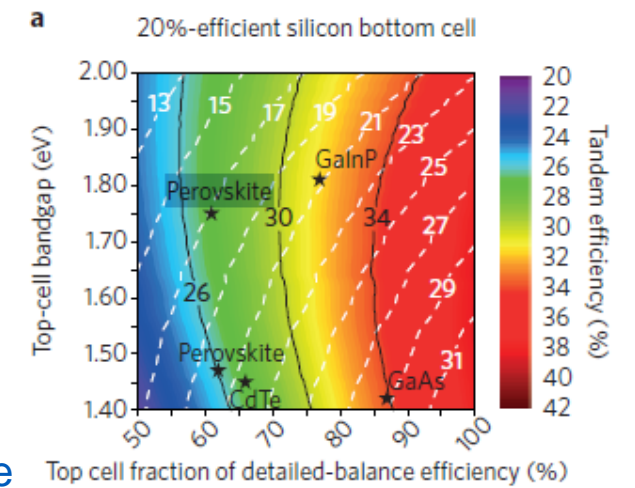


Phototransistor (3T)

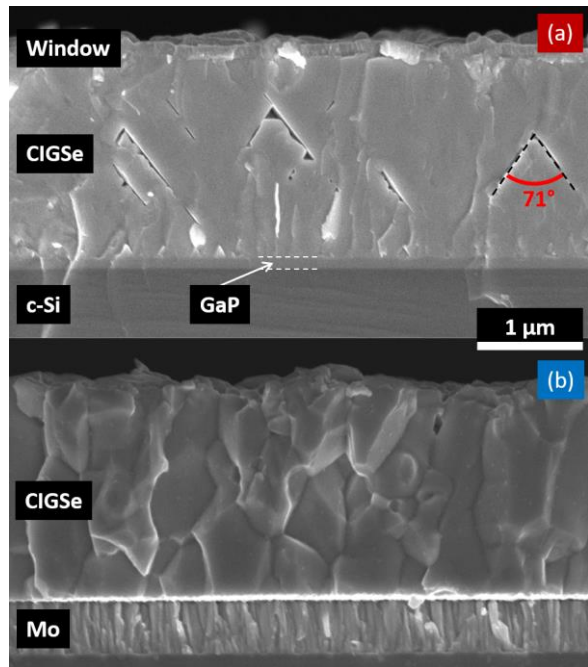
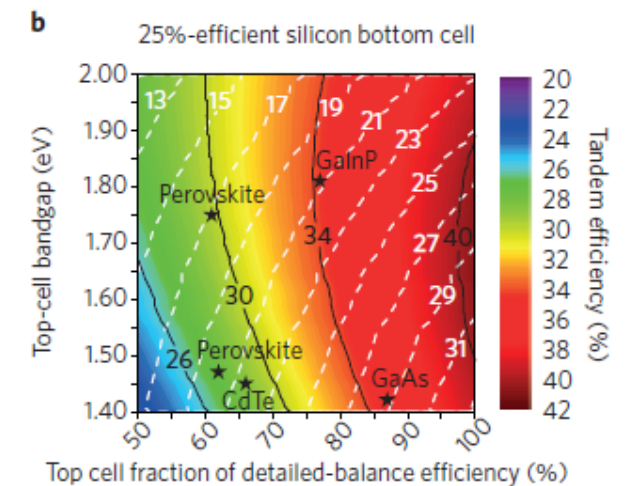
Typiquement

- Même courant dans top et bottom
- 2/3 du voltage dans la top
 - E_g optimaux : 1.1 et 1.8
 - $E_g - V_m > 0.4$ V

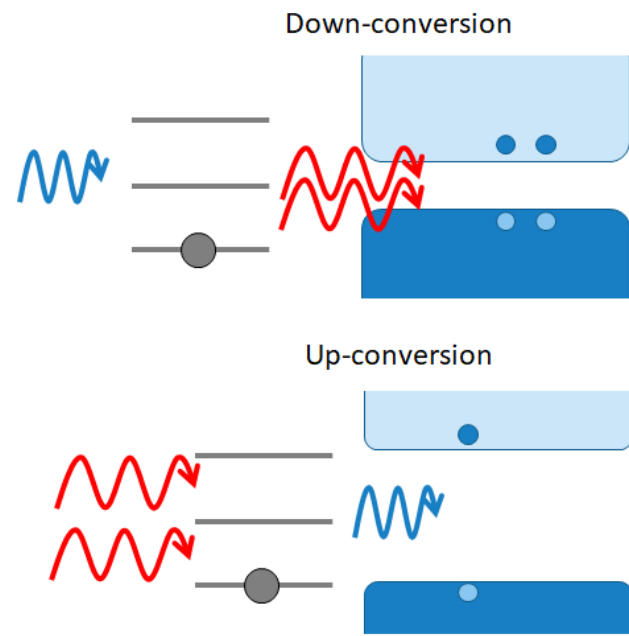
=> Au mieux 1/3 de la puissance vient de la bottom



Grey line:
top cell alone
Black line:
tandem eff

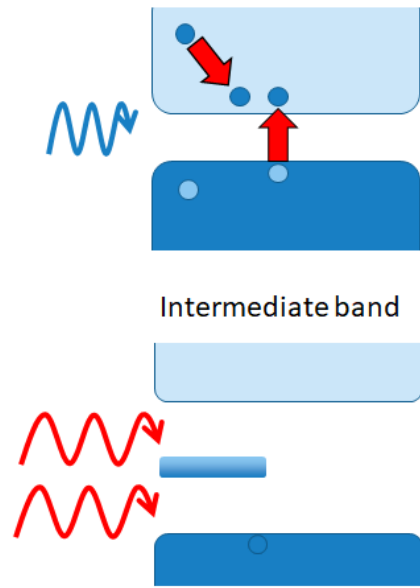


Approches alternatives



© D. Suchet

Multiple exciton generation / singlet fission

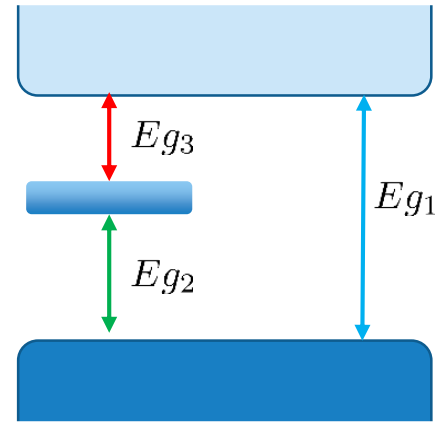
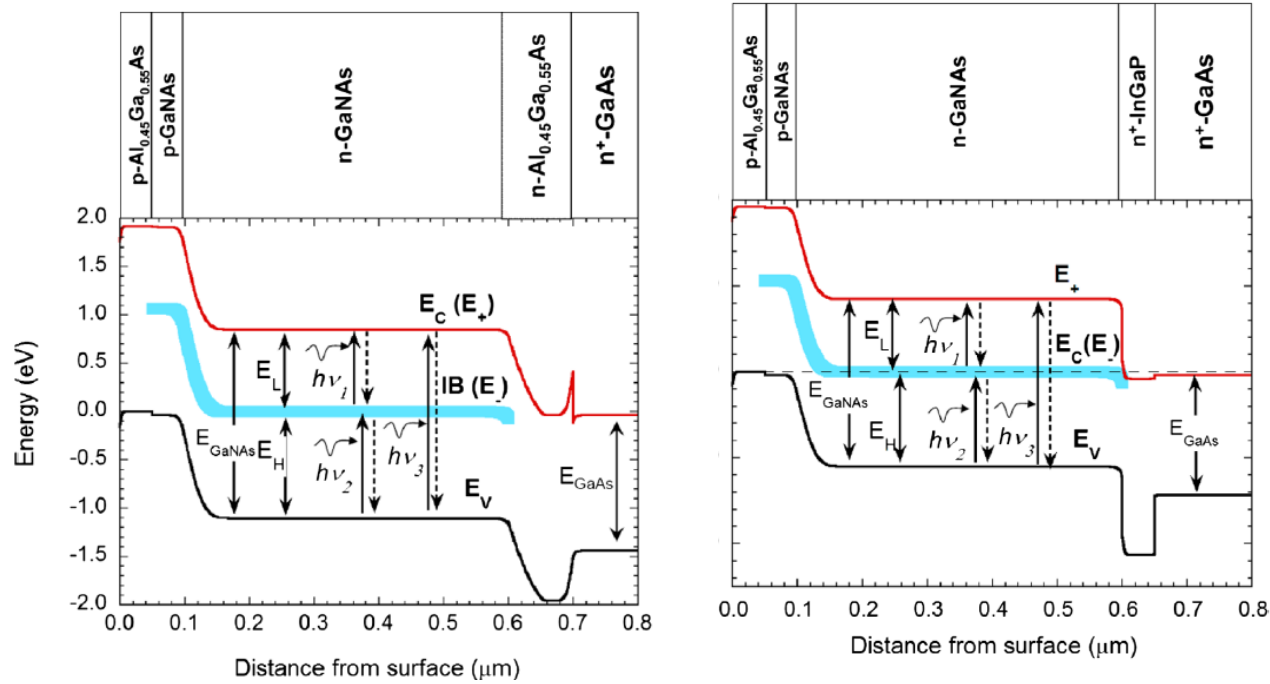


Peut on faire autrement?

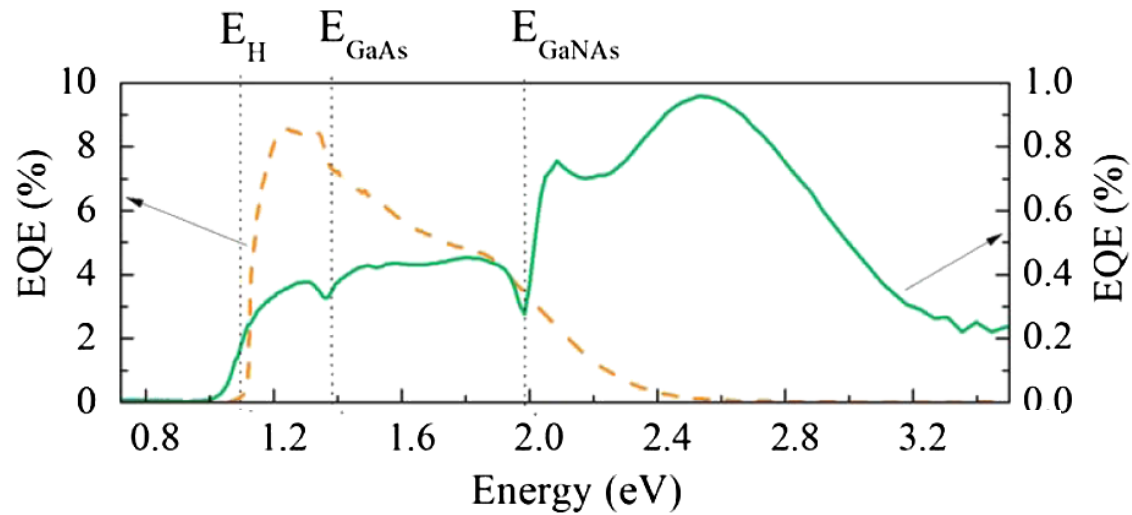
Peut on faire mieux?

Autres approches: IBSC

Lopes et al. *Phys. Rev. Lett.* (2011)



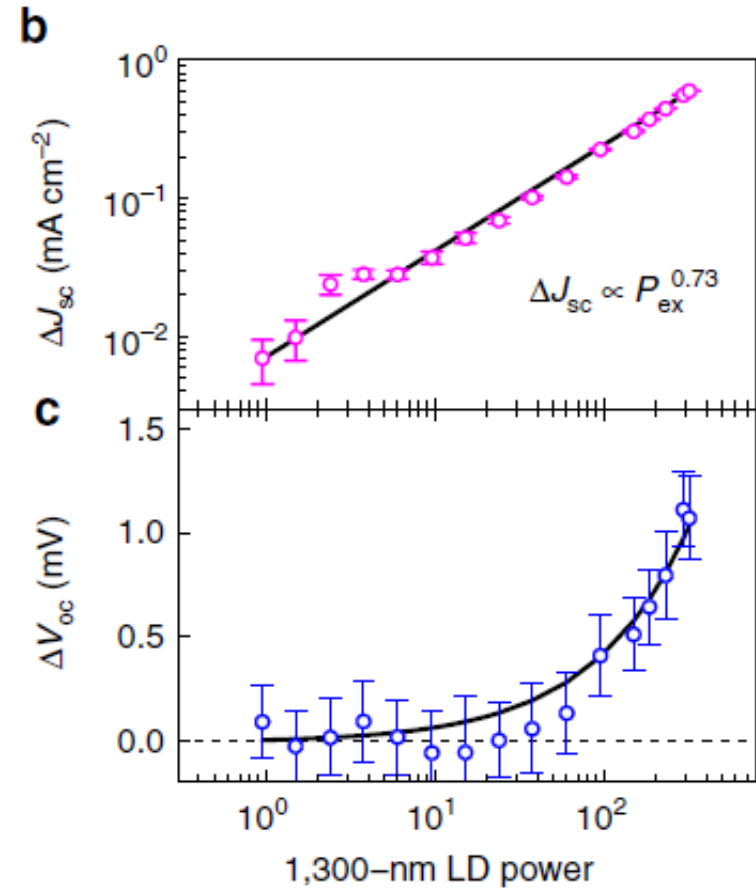
47% (1 sun)
63% (full)



M. Wolf, *Proc. IRE* (1960)

A. Luque and A. Martí, *Phys. Rev. Lett* (1997).

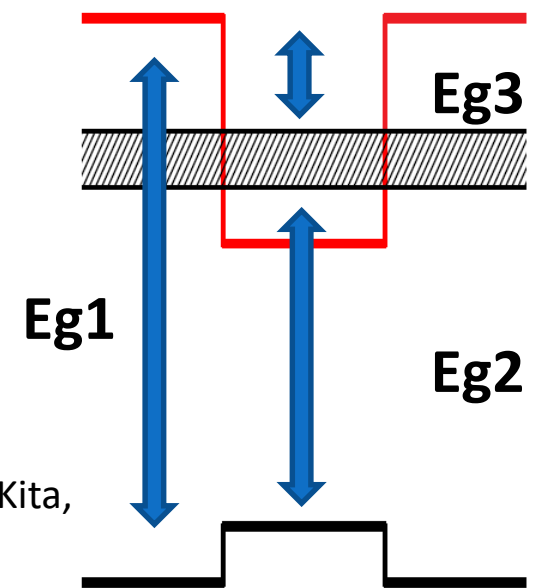
Y. Okada et al. *Appl. Phys. Rev.* (2015)



Effets détectés, mais...

Extrêmement sensible aux imperfections

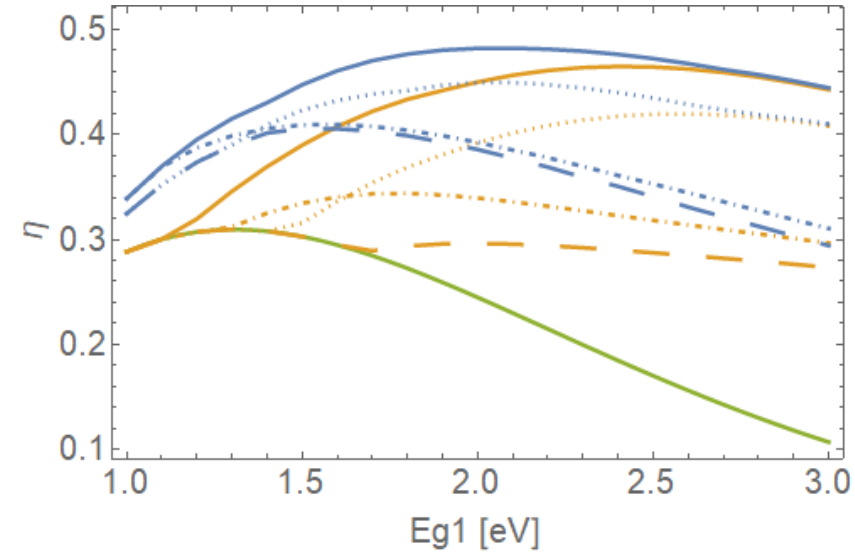
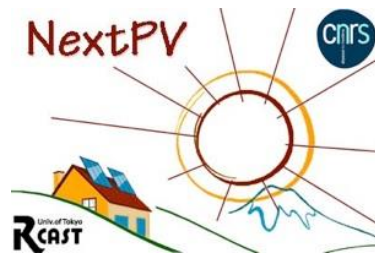
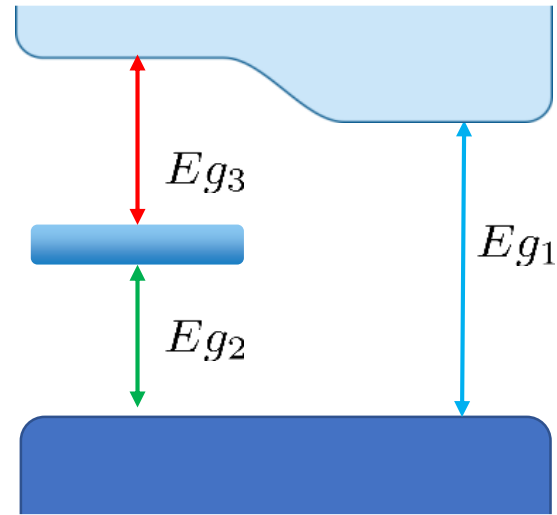
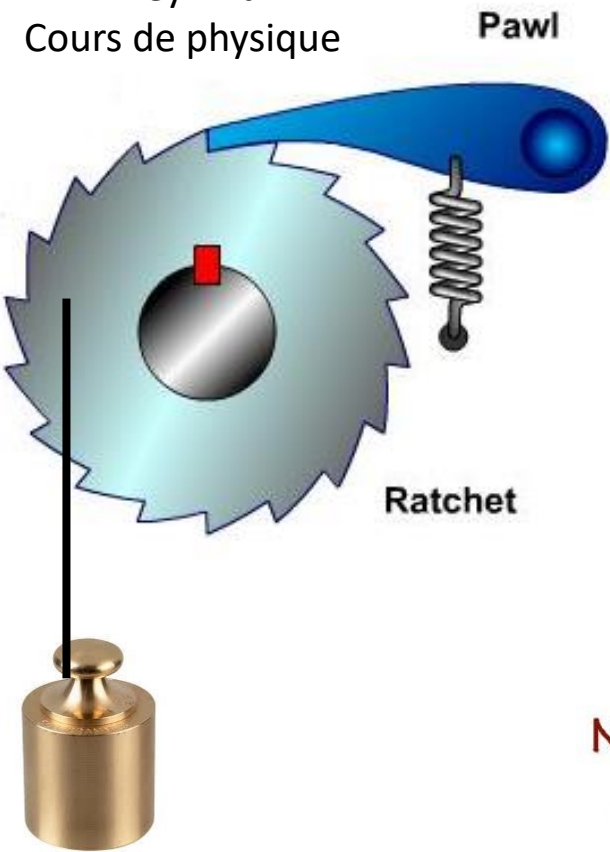
S. Asahi, H. Teranishi, K. Kusaki, T. Kaizu, and T. Kita, *Nature Communications* 8, 14962 (2017).



Ratchet

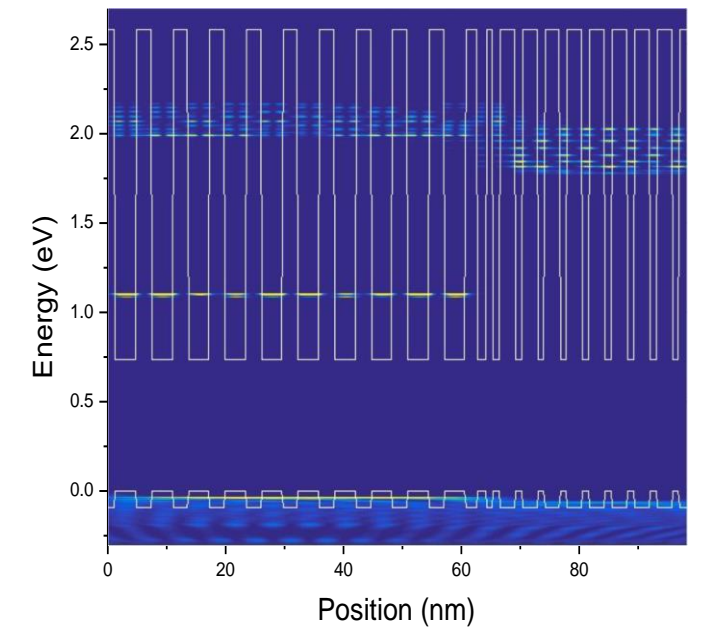
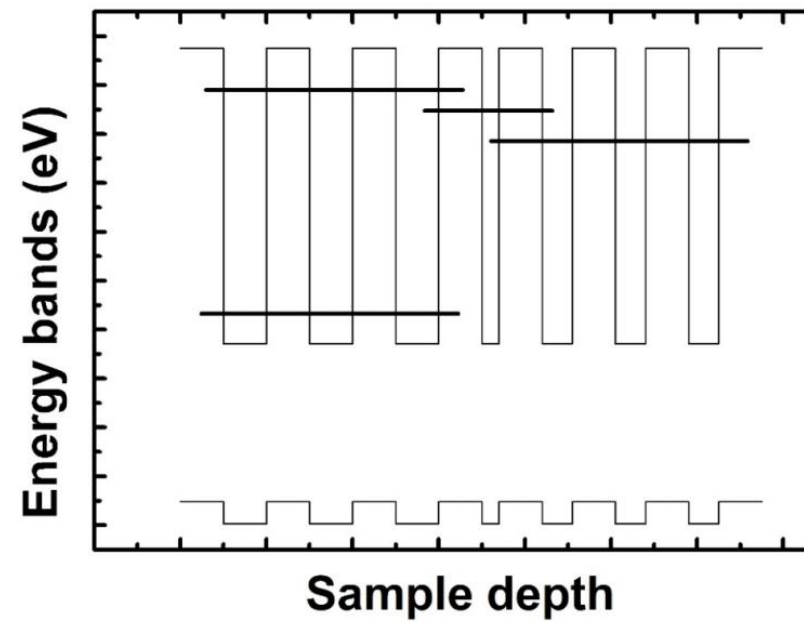


R. Feynman
Cours de physique



Ideal
Non rad.
Narrow abs
Both

Résilience !

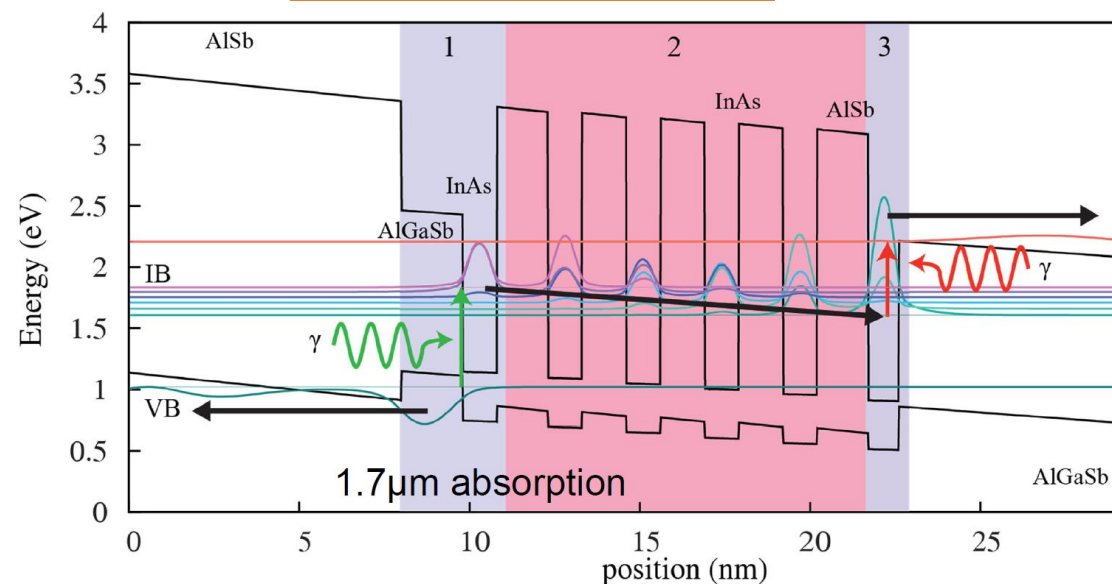


NEGF simulation using
AlAsSb/InGaAs

D Suchet, A. Delamarre, N. Cavassilas, Prog. In PV 26 10 (2018)

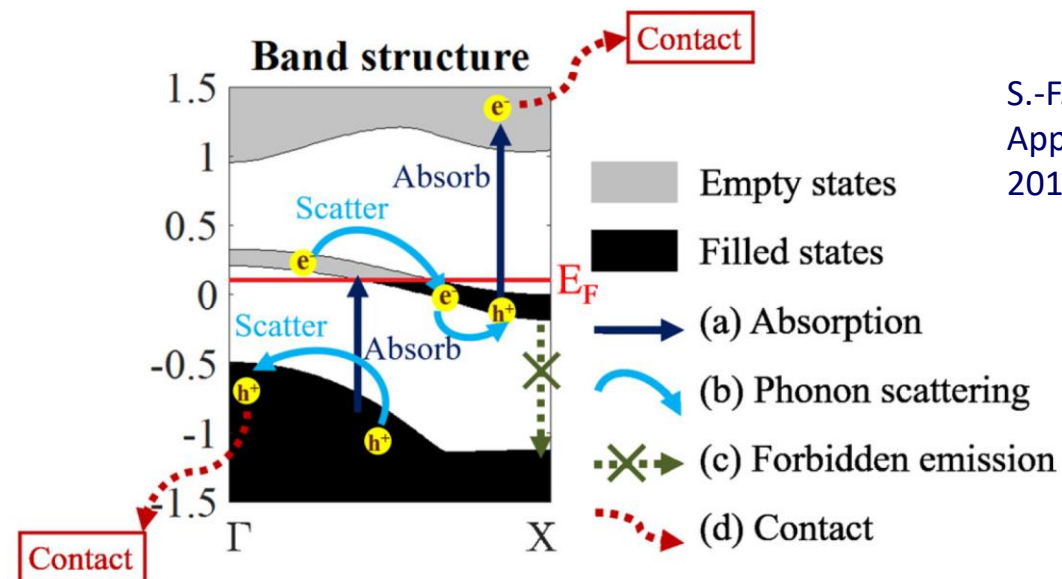
Yoshida et al, Appl Phys Lett (2012)
A. Delamarre, et al, IEEE JPV 8, 6 (2018)

Quantum cascade



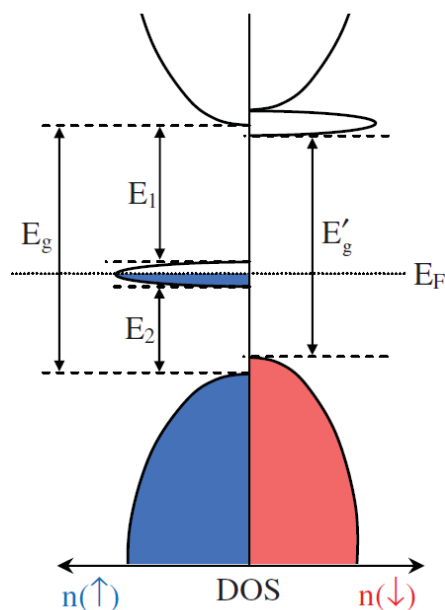
O.J. Curtin, et al, IEEE Journal of Photovoltaics 6, 673 (2016).

2D materials (MoS₂ nano-ribbon)



S.-F. Chen and Y.-R. Wu, Applied Physics Letters 110, 201109 (2017).

Compounds with transition metals



P. Olsson, C. Domain, and J.-F. Guillemoles, Physical Review Letters 102, (2009).

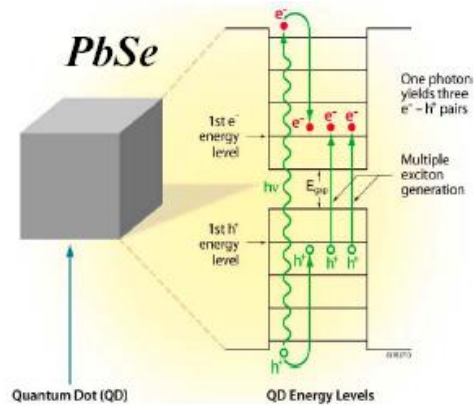
Autres approches: MEG

Science 16 December 2011, Vol. 334 no. 6062 pp.

1530-1533; DOI: 10.1126/science.1209845

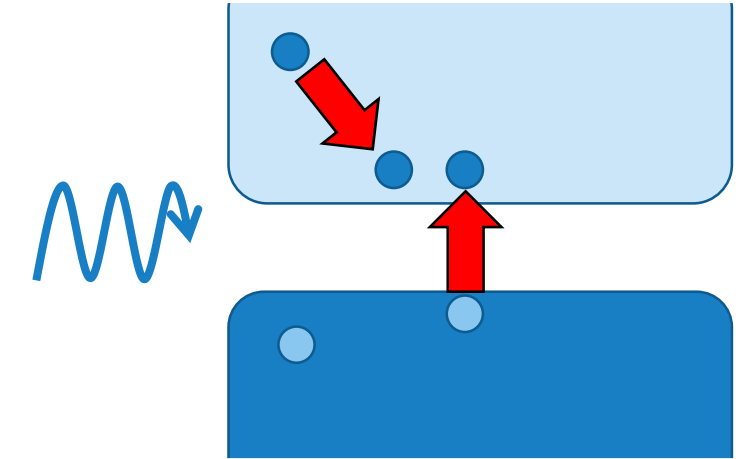
Peak External Photocurrent Quantum Efficiency Exceeding 100% via MEG in a Quantum Dot Solar Cell

Octavi E. Semonin,^{1,2} Joseph M. Luther,¹ Sukgeun Choi,¹ Hsiang-Yu Chen,¹ Jianbo Gao,^{1,3} Arthur J. Nozik,^{1,4*} Matthew C. Beard^{2*}

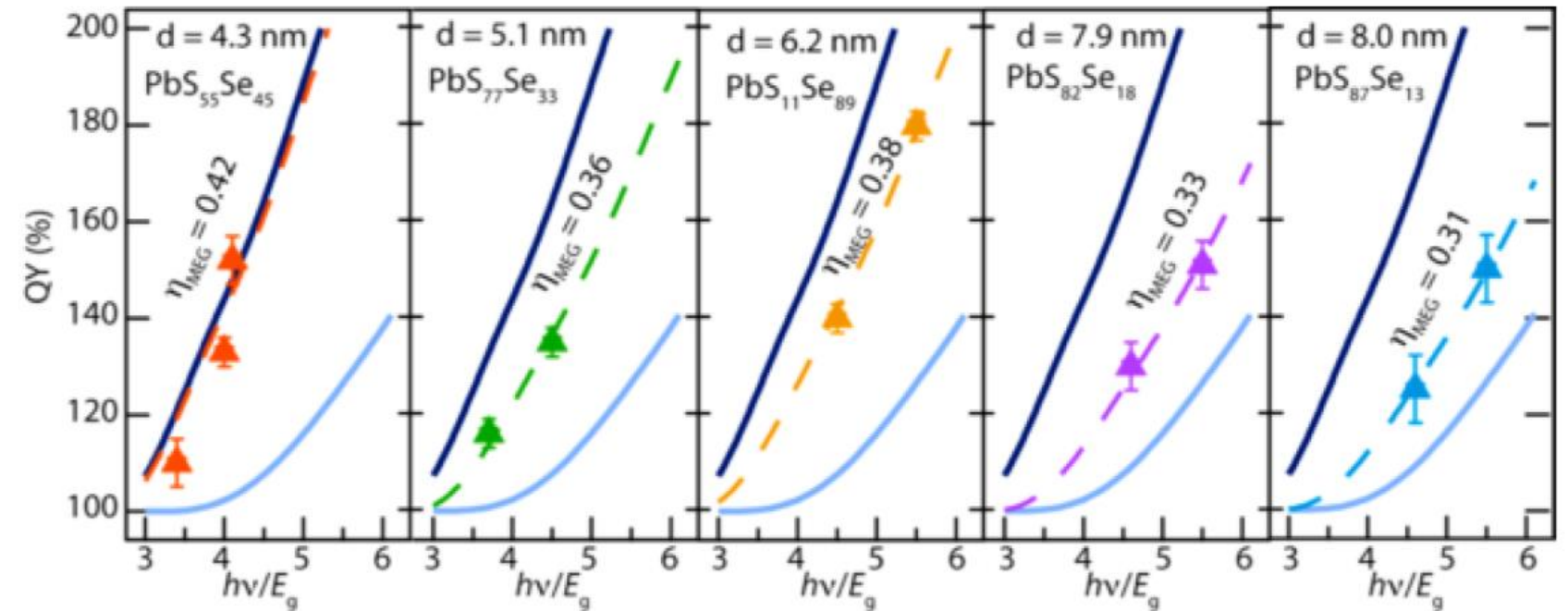
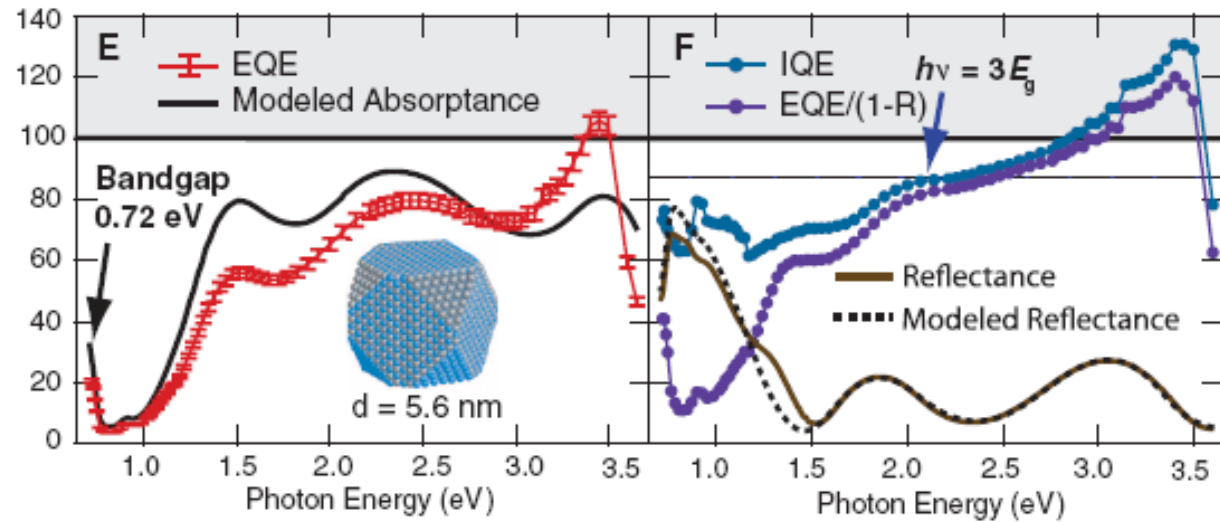


Existe dans tous les matériaux

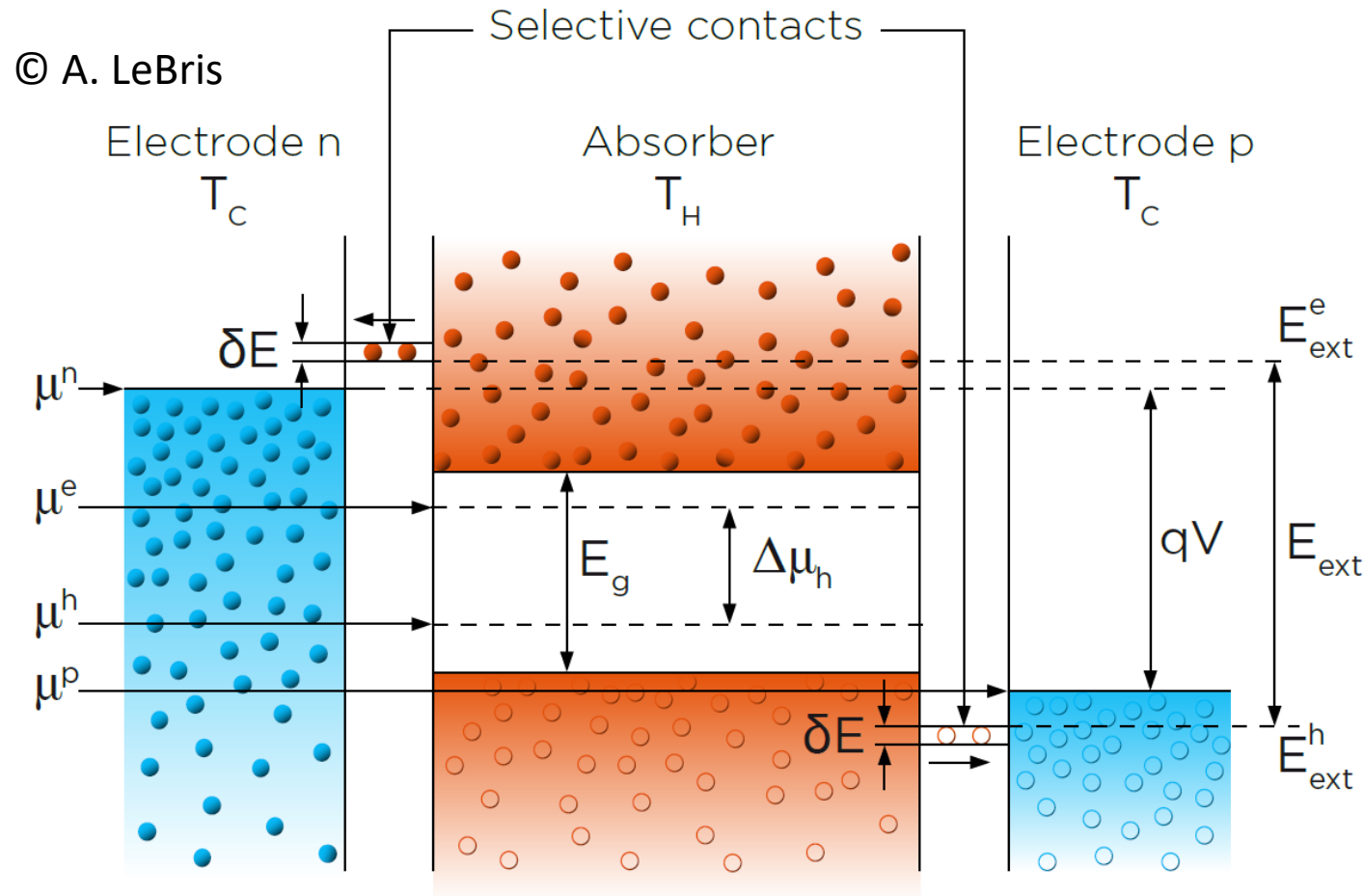
Mis en évidence dans des cellules PV



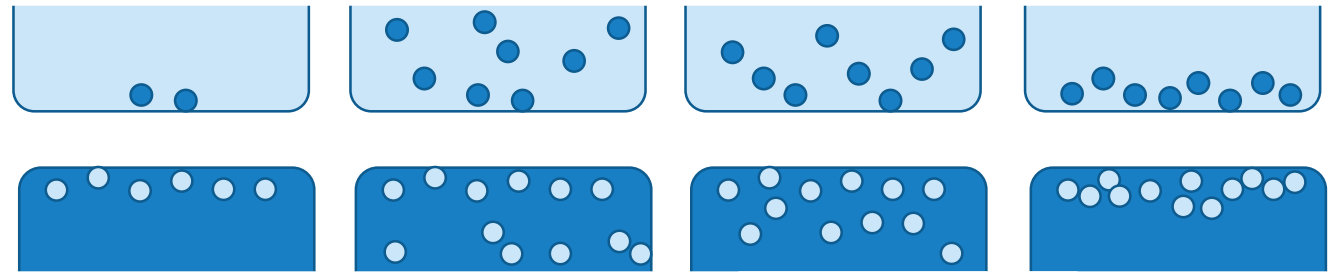
44% (1 sun)
85% (full)



Concept de cellule « à porteurs chauds »



Extract carriers before full thermalization
Narrow width energy selective contacts



68% (1 sun)
86% (full)

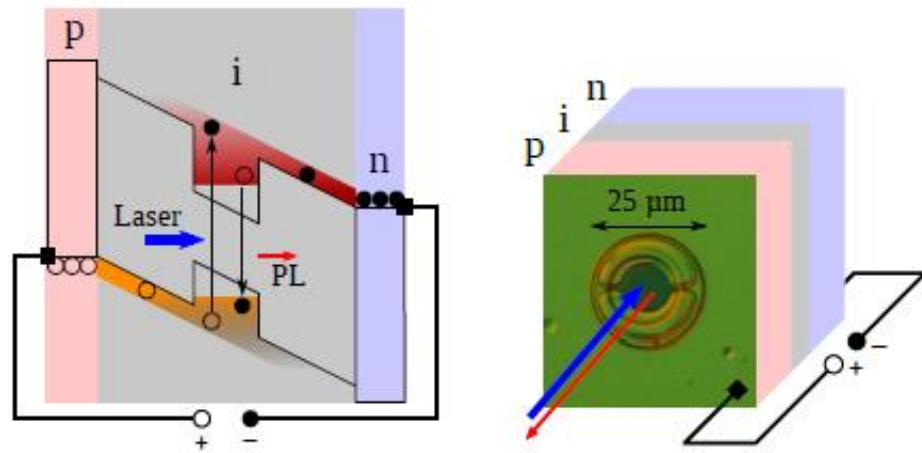
Ross & Nozik, *J. Appl. Phys* (1982)
Würfel, *Sol Mat* (1997)

L'extraction des porteurs se fait avant thermalisation complète

Avec des contacts sélectifs en énergie, le gap ne limite plus le Voc

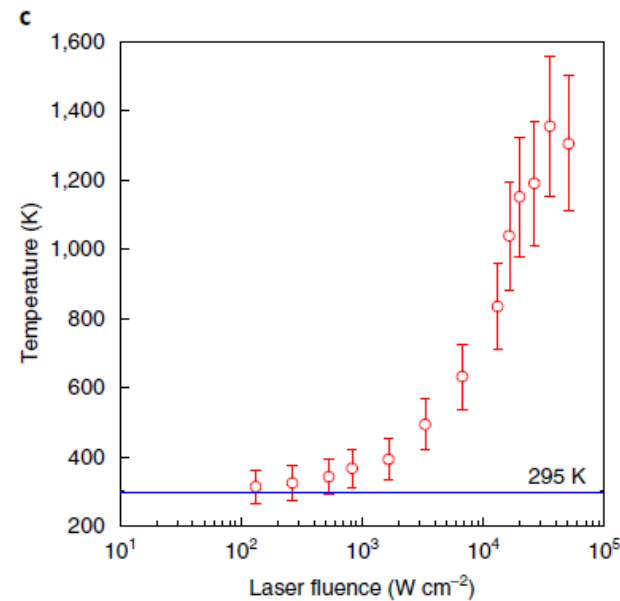
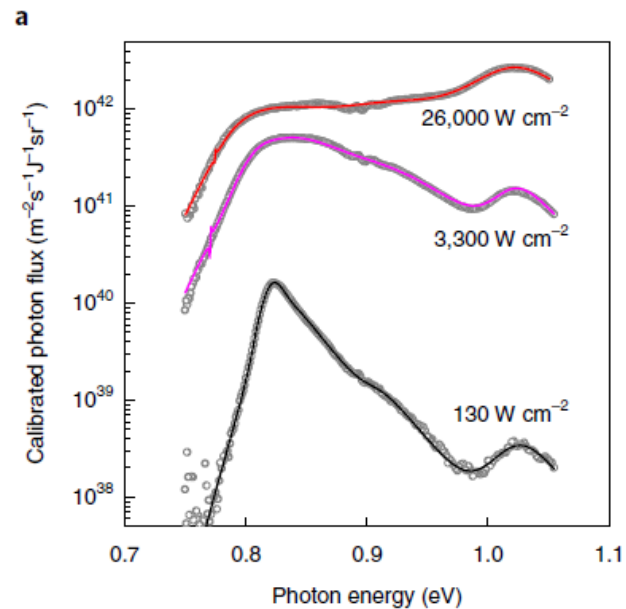
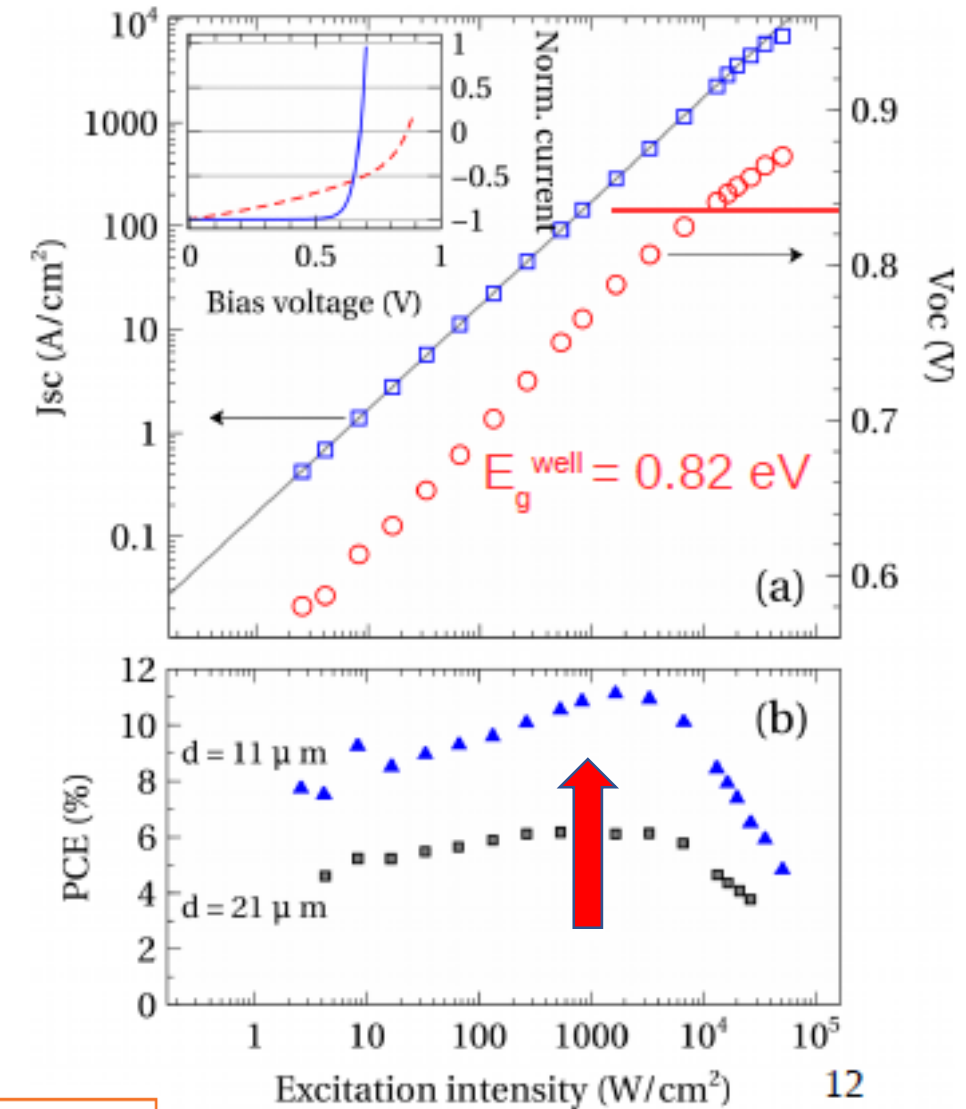
Concept associant effet photovoltaïque et thermoélectrique

Autres approches: HCSC



Thermalisation ralentie dans les nanostructures et sous fort flux

⇒ Dispositifs très fins



Cellules solaires avec un optimum à 15000 suns et dont la température de porteurs est de 600K

ARTICLES

<https://doi.org/10.1038/s41560-018-0106-3>

nature energy

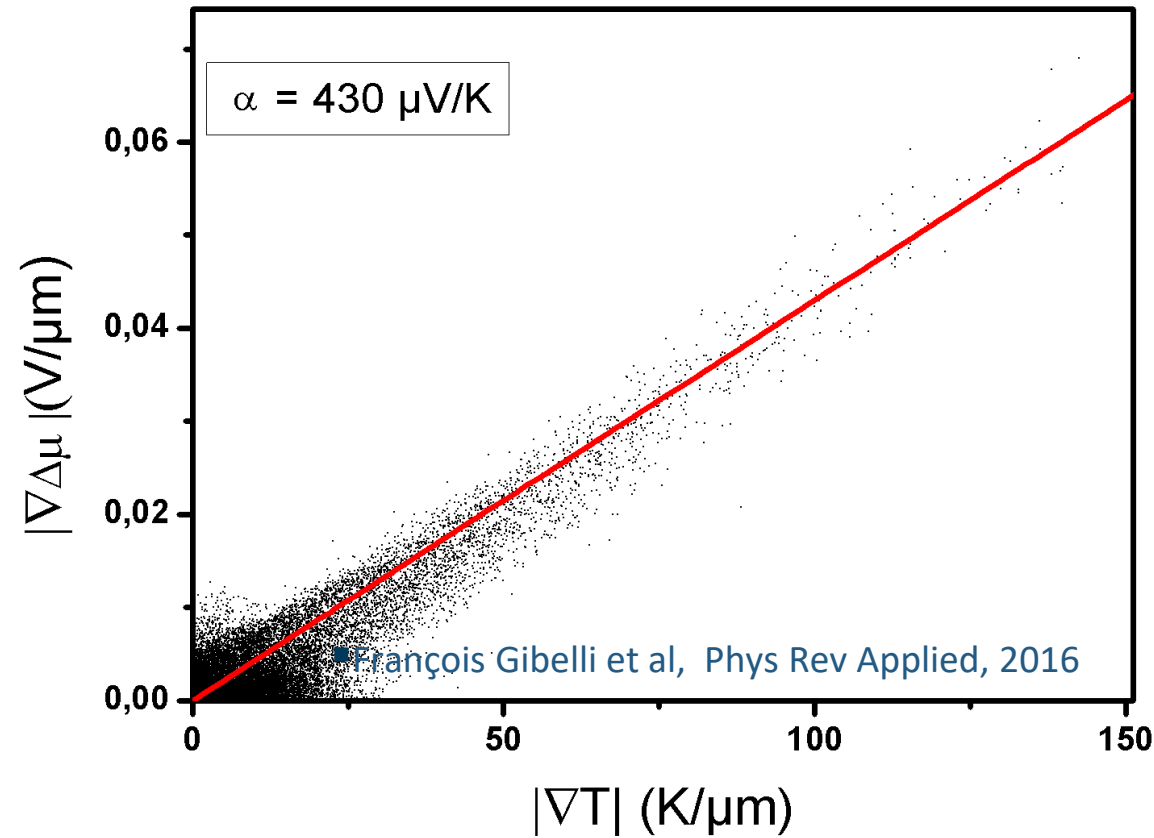
Quantitative experimental assessment of hot carrier-enhanced solar cells at room temperature

Dac-Trung Nguyen¹, Laurent Lombez^{1,2*}, François Gibelli^{1,2}, Soline Boyer-Richard³, Alain Le Corre³, Olivier Durand³ and Jean-François Guillemoles^{1,2}

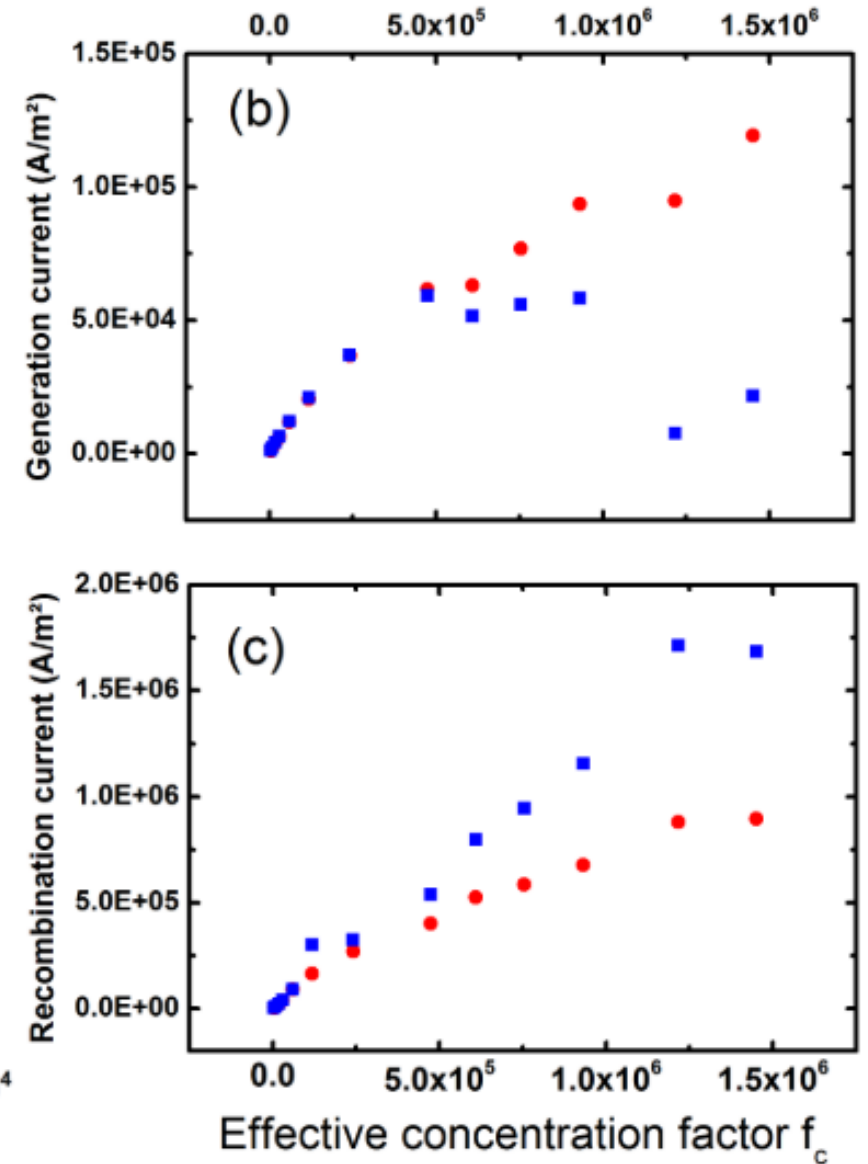
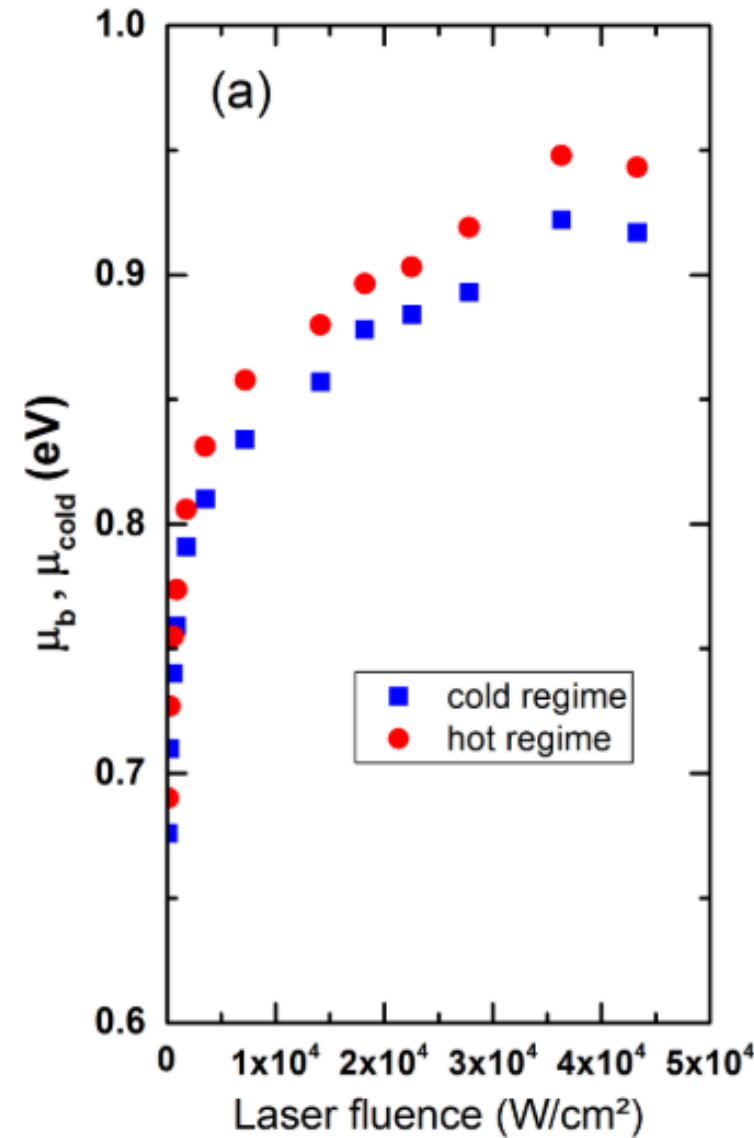
Myriam Paire et al., Energy Environ. Sci., 2011
A. Lebris et al., Energy Environ. Sci., 2012
Trung Dac Nguyen et al, Nat Energy 2018

33

Couplage thermique-PV



$$\Phi_{\text{PL}}(E) = \frac{A(E)E^2}{4\pi^2 \hbar^3 c_0^2} \frac{1}{\exp\left(\frac{E - \Delta\mu}{kT}\right) - 1}$$



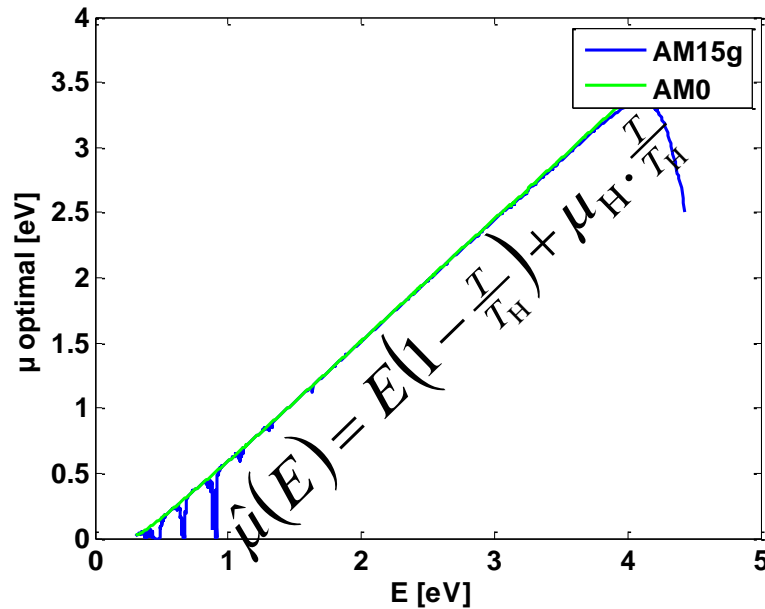
Cold vs Hot: Half the generation, twice the recombination

Trung Dac Nguyen et al, Nat Energy 2018

Generalization (multi-thermal)

- Let's define:

$$\hat{\mu}(E) = E\left(1 - \frac{T}{T_H}\right) + \mu_H \cdot \frac{T}{T_H} = (E - E_{\text{ext}})\left(1 - \frac{T}{T_H}\right) + qV$$



- This yields

- ✓ the same spectral power at ambient as the Bose distribution at μ_H and T_H
- ✓ the same useable work per photon at room temperature
- ✓ NB: the linear relationship of $\mu(E)$ fits nicely (for a proper choice of μ_H and T_H) the optimal $\mu(E)$ curve

- NB: non thermal photon vs electron QY reads**

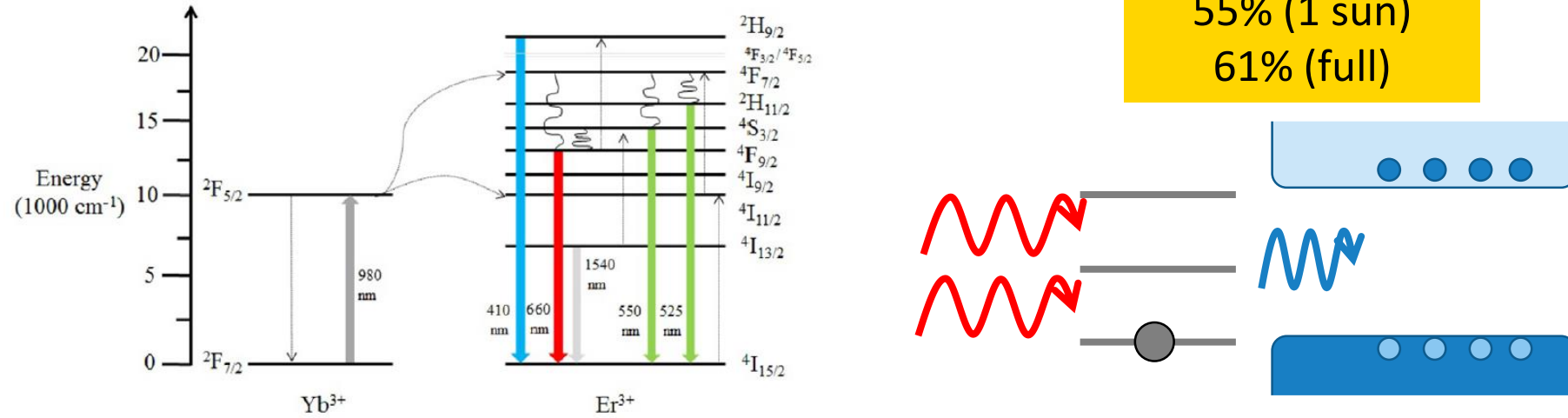
$$\mu_H(E) = \left[qV - E_{\text{ext}} \left(1 - \frac{T}{T_H}\right) \right] \frac{T_H}{T} = QY \cdot qV + S \cdot \Delta T$$

Yields close to optimal efficiencies (85%)

Autres approches: Conversion de photons

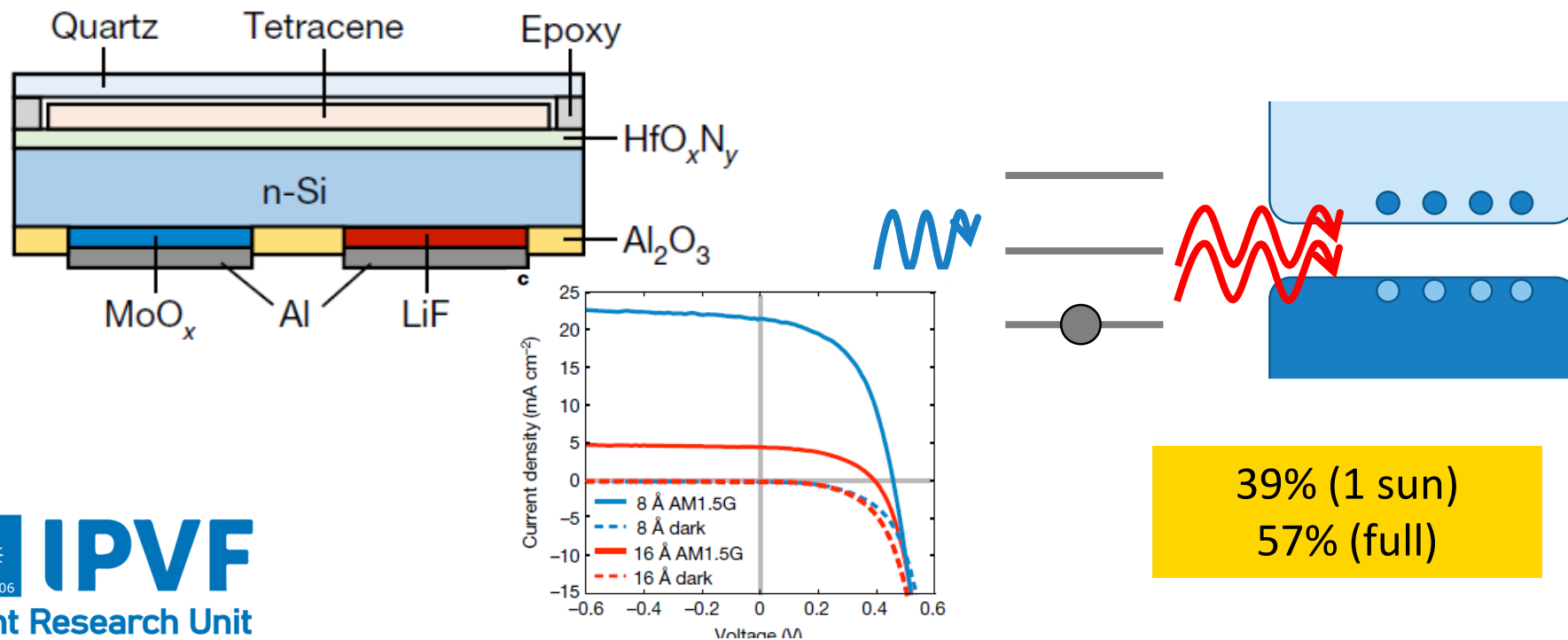
Mostly rare earth (QD and TTA also possible)

J. Day et al. *Renewable Energy* (2019)



Tetracene on Silicon solar cell

Einzinger et al *Nature* (2019)

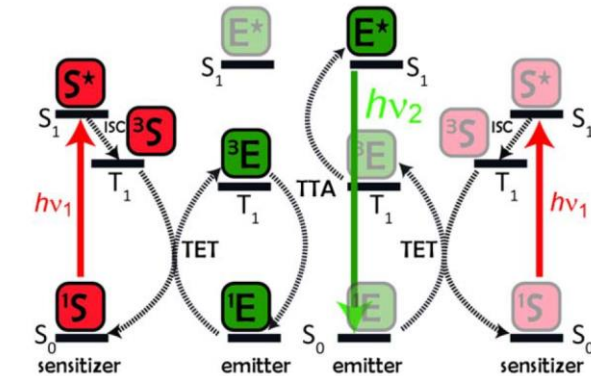


Conversion ascendante: facile à détecter, mais nécessite souvent des effets coopératifs

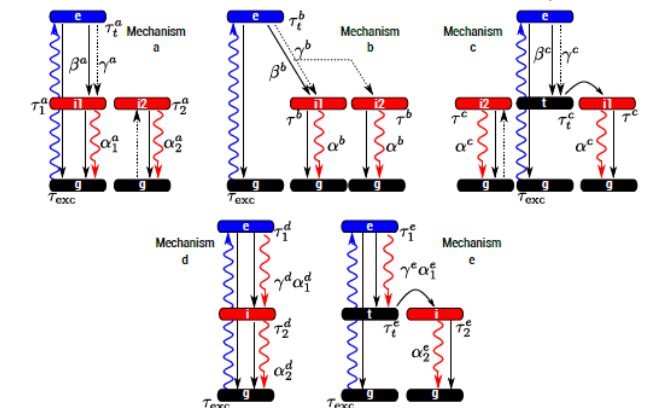
Conversion descendante: plus difficile à détecter

Triplet-triplet annihilation

Advanced Concepts in Photovoltaics (Royal Society of Chemistry, Cambridge, UK, 2014).



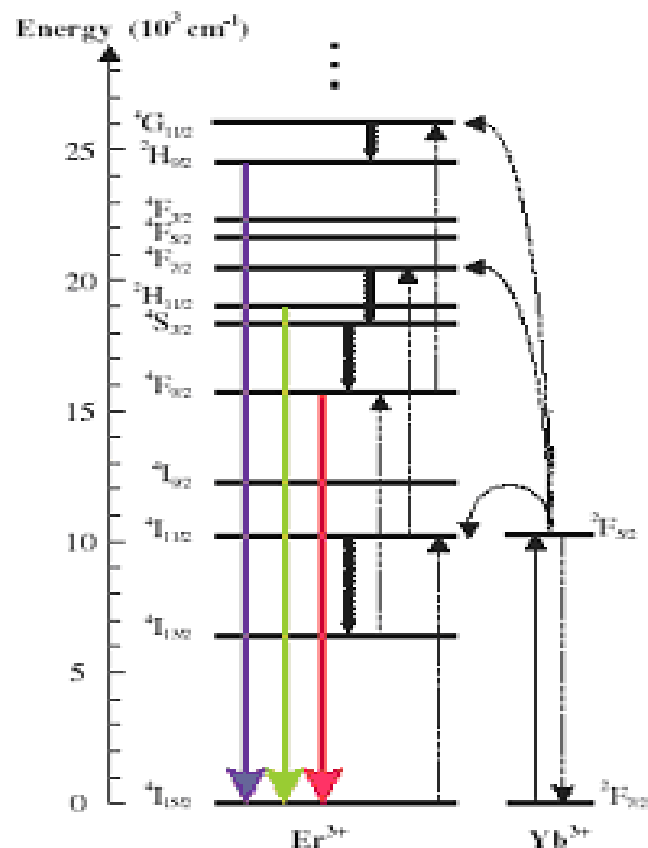
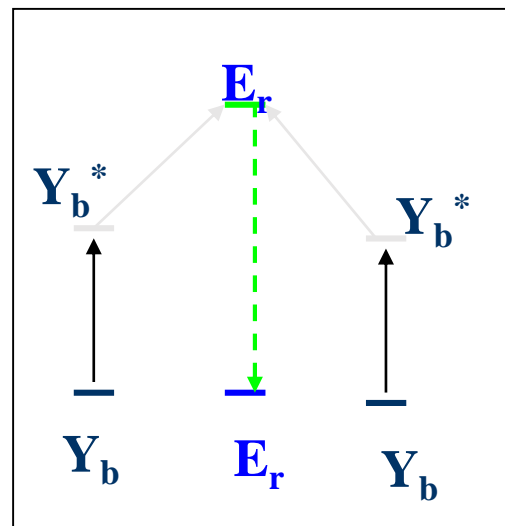
M. Löning, D. Suchet, L. Lombez and J.-F. Guillemoles, *J. Chem. Phys.* 154, 014201 (2021)



JF Guillemoles, UMR IPVF-9/02/2022

Exemples

APTE



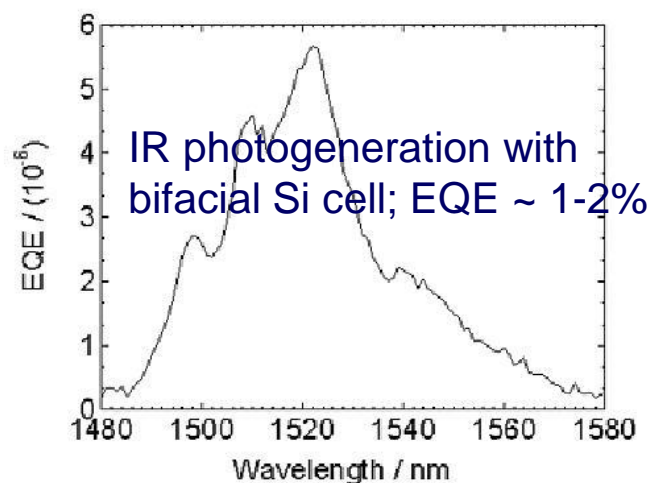
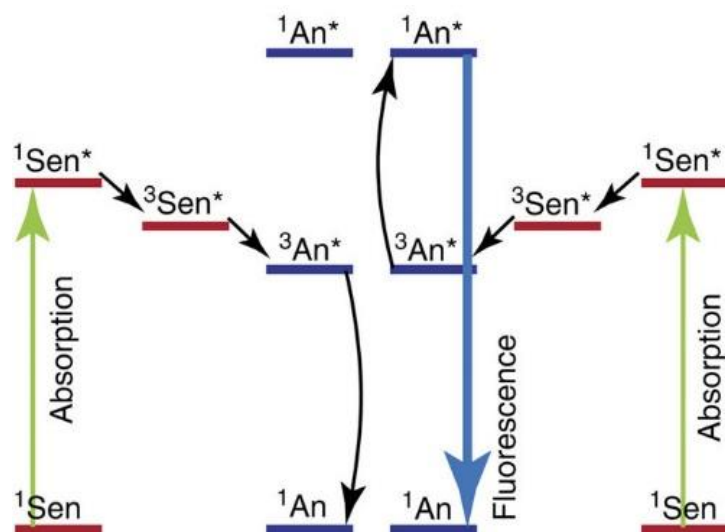
Existing : ~ 5% of IR photons converted

Molecular/RE systems

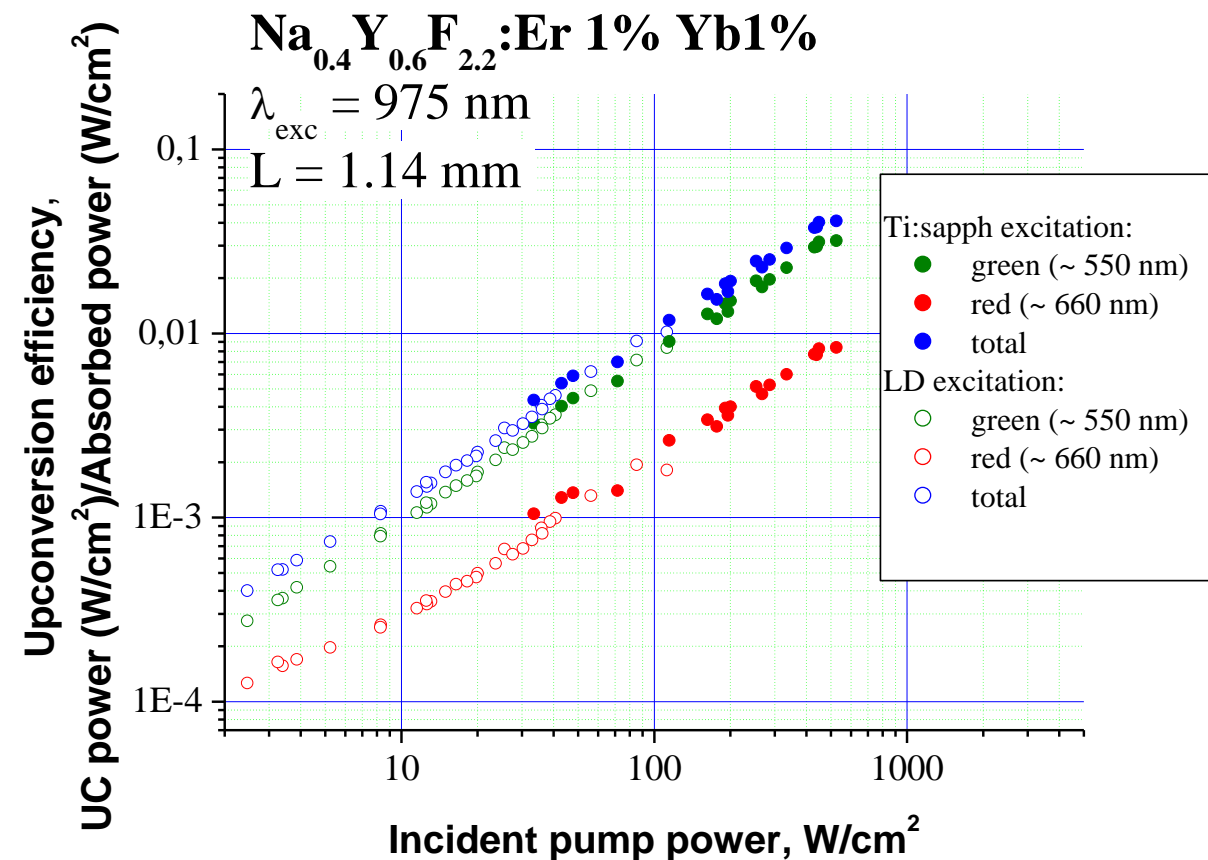
Photon upconversion with directed emission, [K. Börjesson, Chalmers university, Nature Communications 7, 12689 \(2016\)](#)

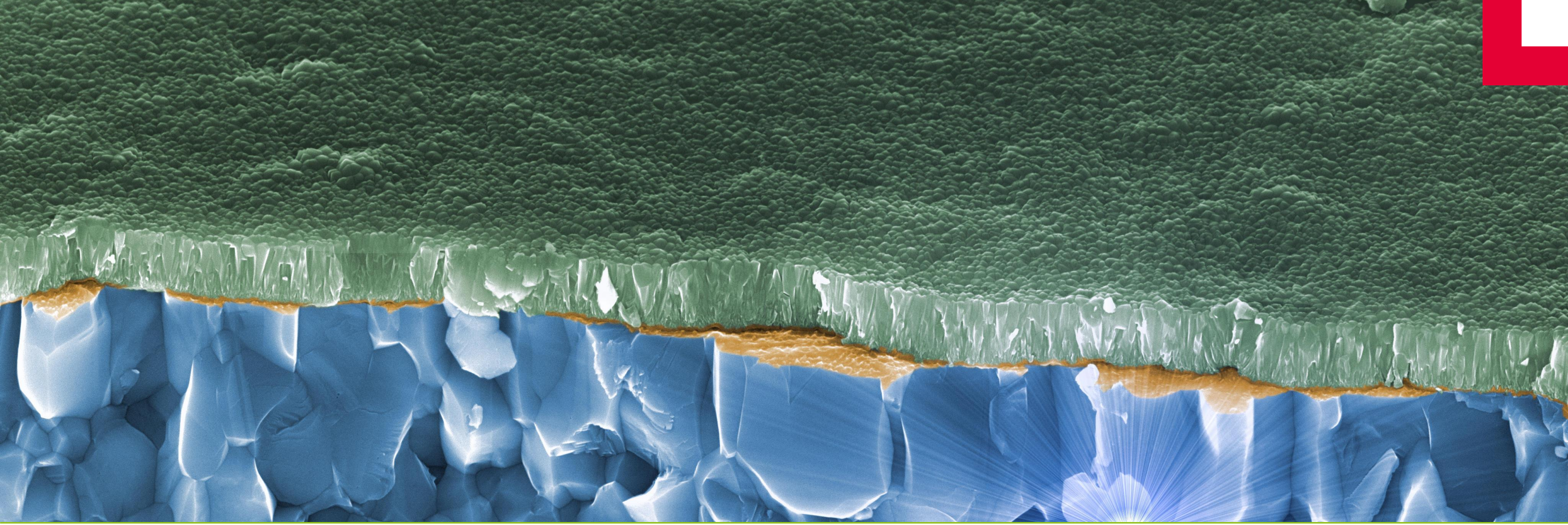
Oxydes (CHREA 95) , fluorides (2003), eff 2.5% (x 250)

F. Auzel 1995



T. Trupke, 2004





Soutenabilité

Soutenabilité : le défi TW

Energie primaire mondiale : 19 TW (2019 BP Stat review 2020)

dont 7,5 TW électrique

PV installé en 2020: 700 GW

=> environ 5000 km²

=> ~ 50 Mt de matériaux (verre)

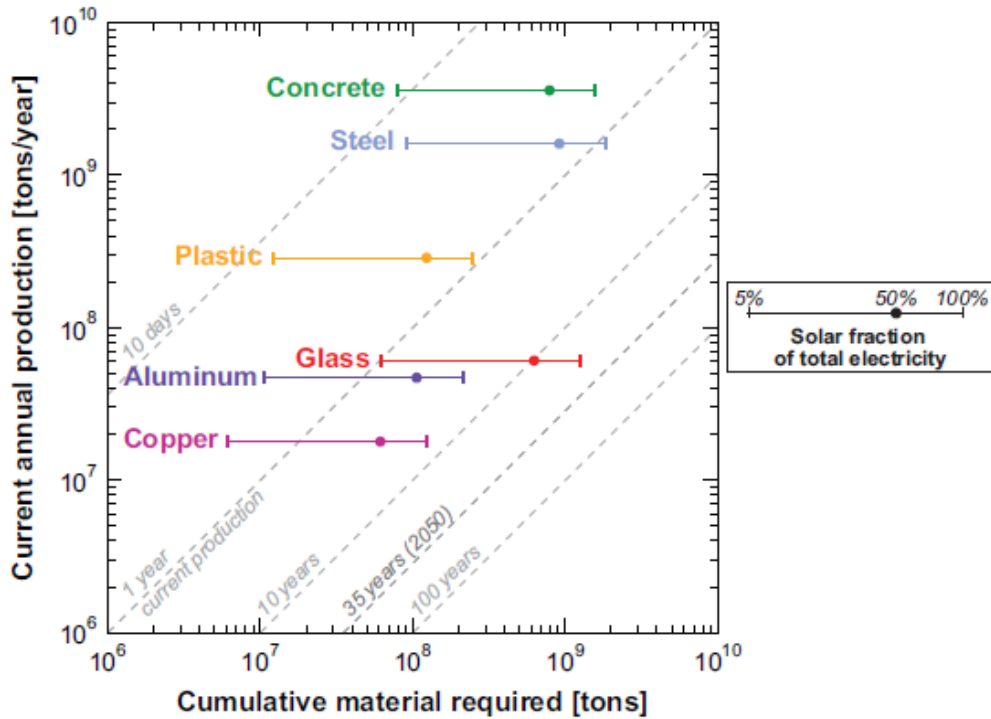
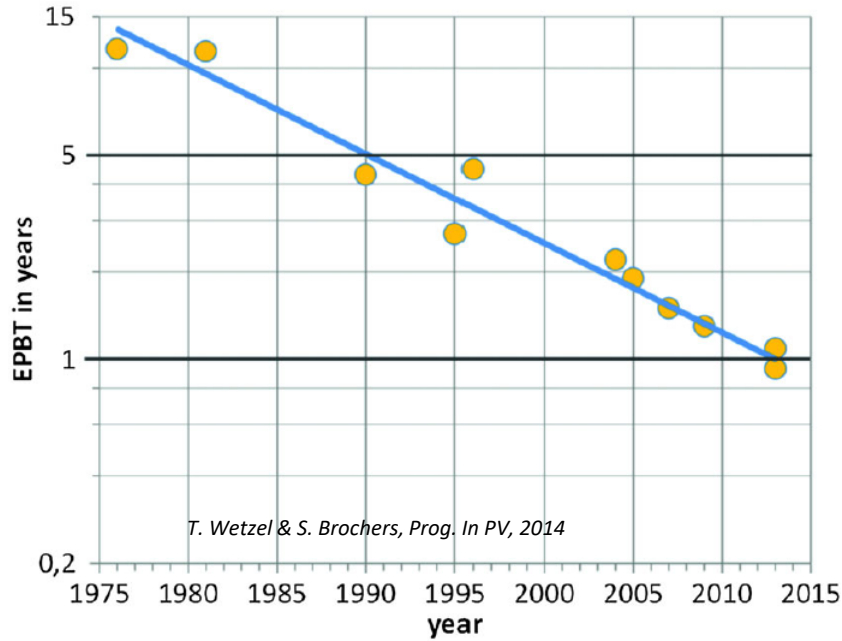
Abondance: au delà des éléments (Si)

Purification (2 Mt c-Si)

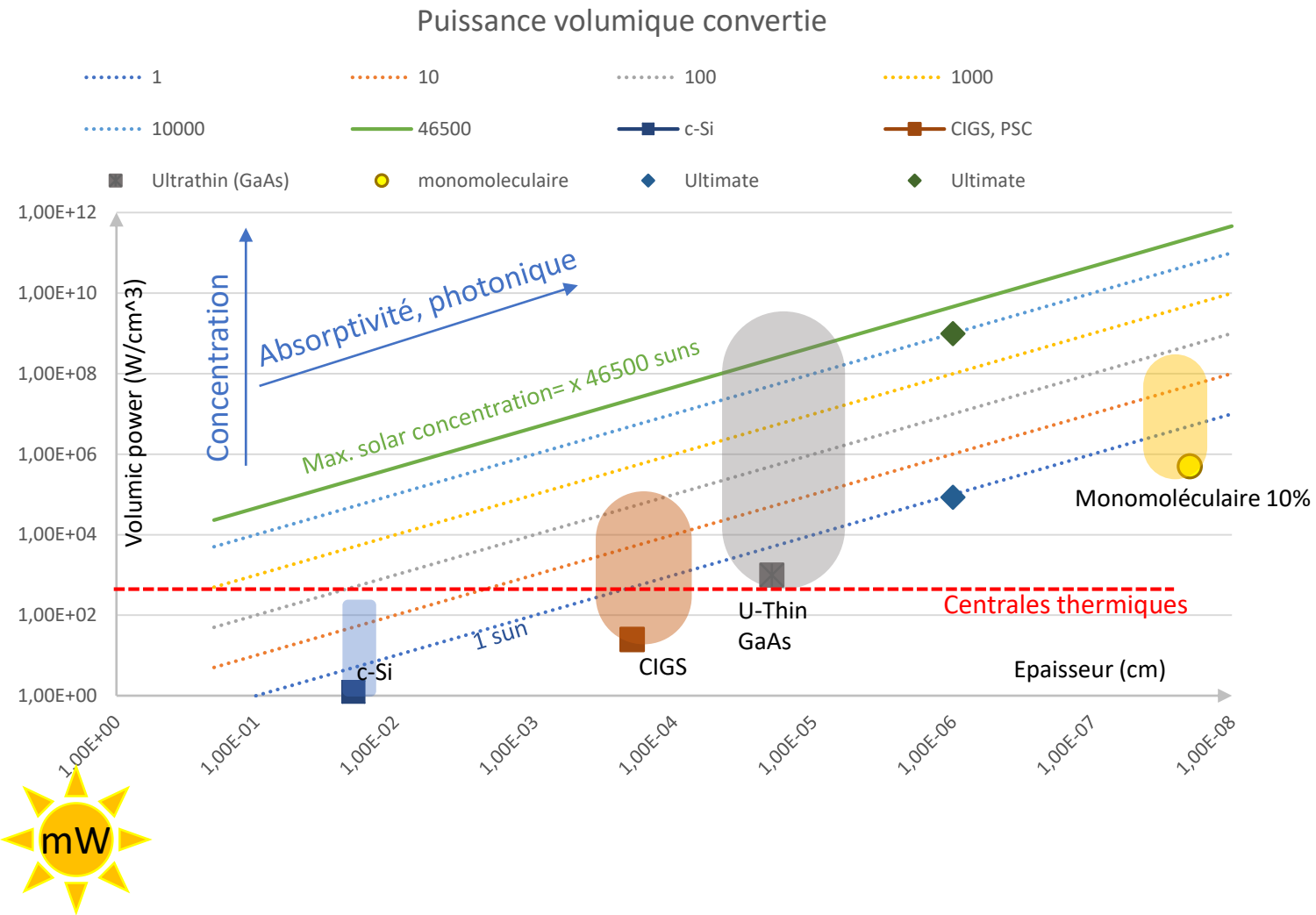
Contacts Ag (50% demande), Pb, ...



Faire évoluer les procédés de fabrication;
Economie d'atomes



Ordres de grandeurs



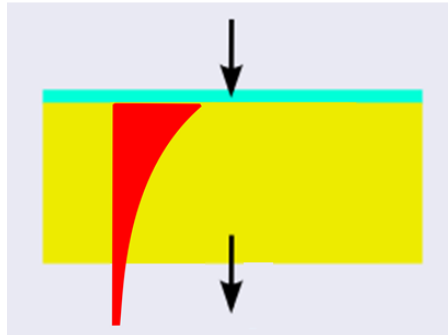
Quelle puissance volumique dans les systèmes de conversion chaleur => électricité?

- Centrales thermiques et couches minces: 100-300 W/cm³
- Rendement: facteur 4 possible
- Photonique: facteur 10-100 possible
- Concentration: facteur 46500 max
- Valeurs ultimes au GW/cm³

=> Les matériaux actifs ne sont pas un problème fondamental

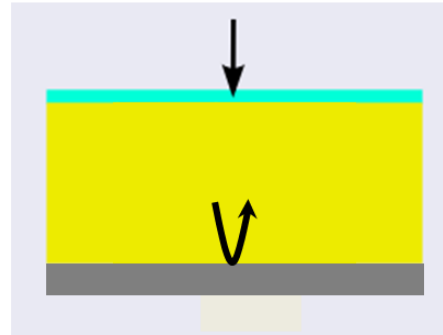
Reduire la quantité de matériaux par la photonique

Single pass



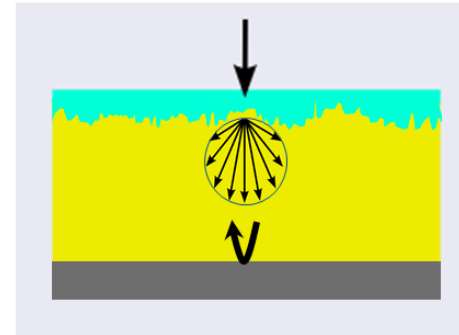
$$F = 1$$

Double pass



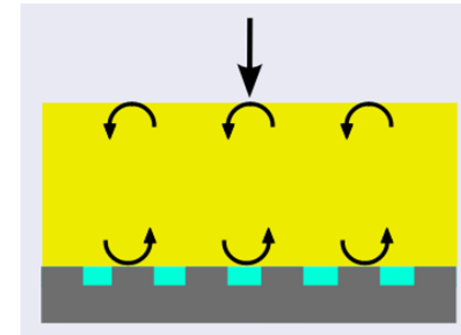
$$F = 2$$

Lambertian



$$F = 4n^2$$

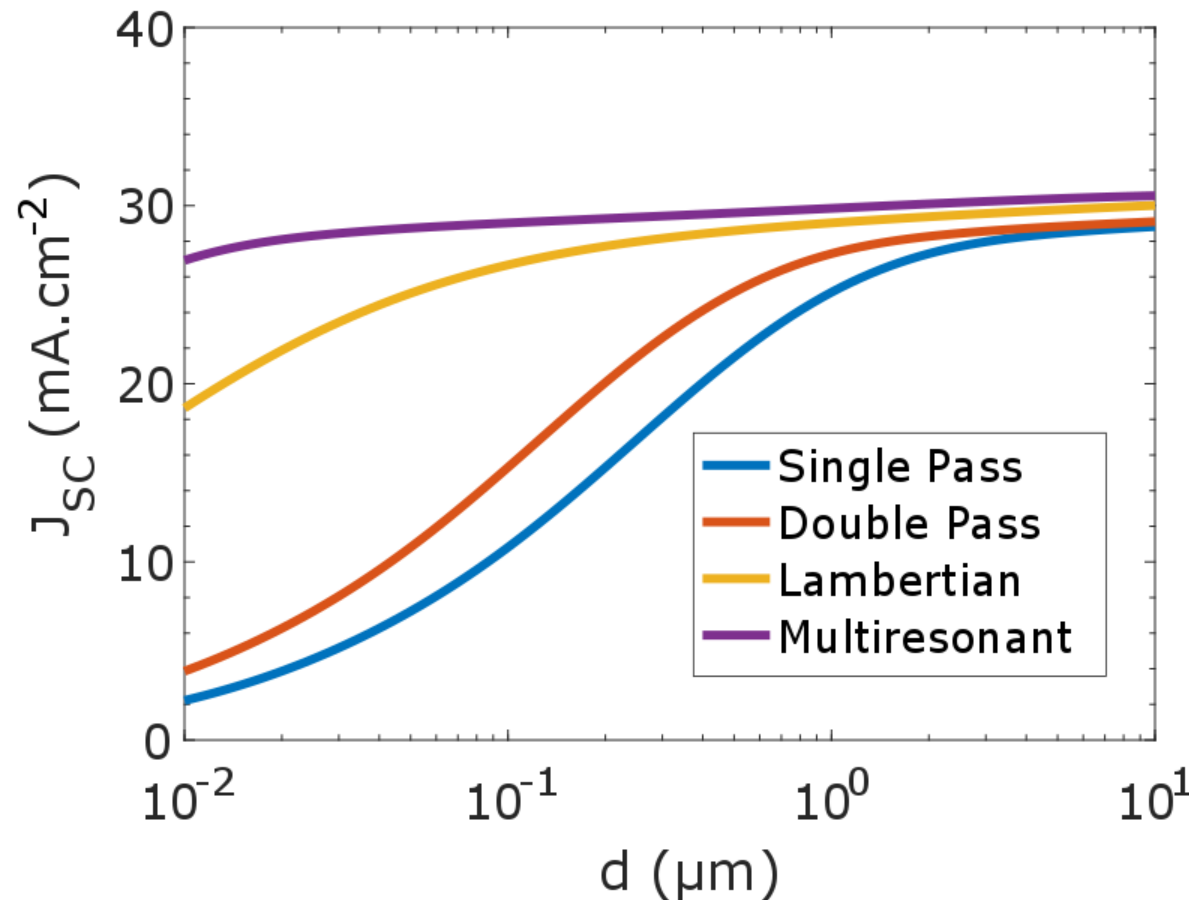
Multi-resonant



$$F = 4\pi n^2$$

≈ 150

Effective thickness: $d_{eff} = F \cdot d$
 F : light path enhancement



Modèle de Yablonovitch

$J_{sc} = 28 \text{ mA.cm}^{-2}$ dans GaAs:
 $2 \mu\text{m} \Rightarrow 30 \text{ nm!}$

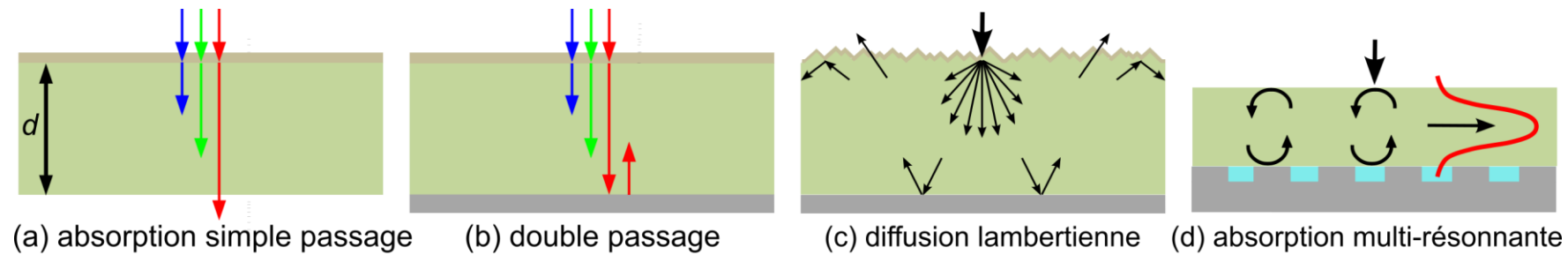
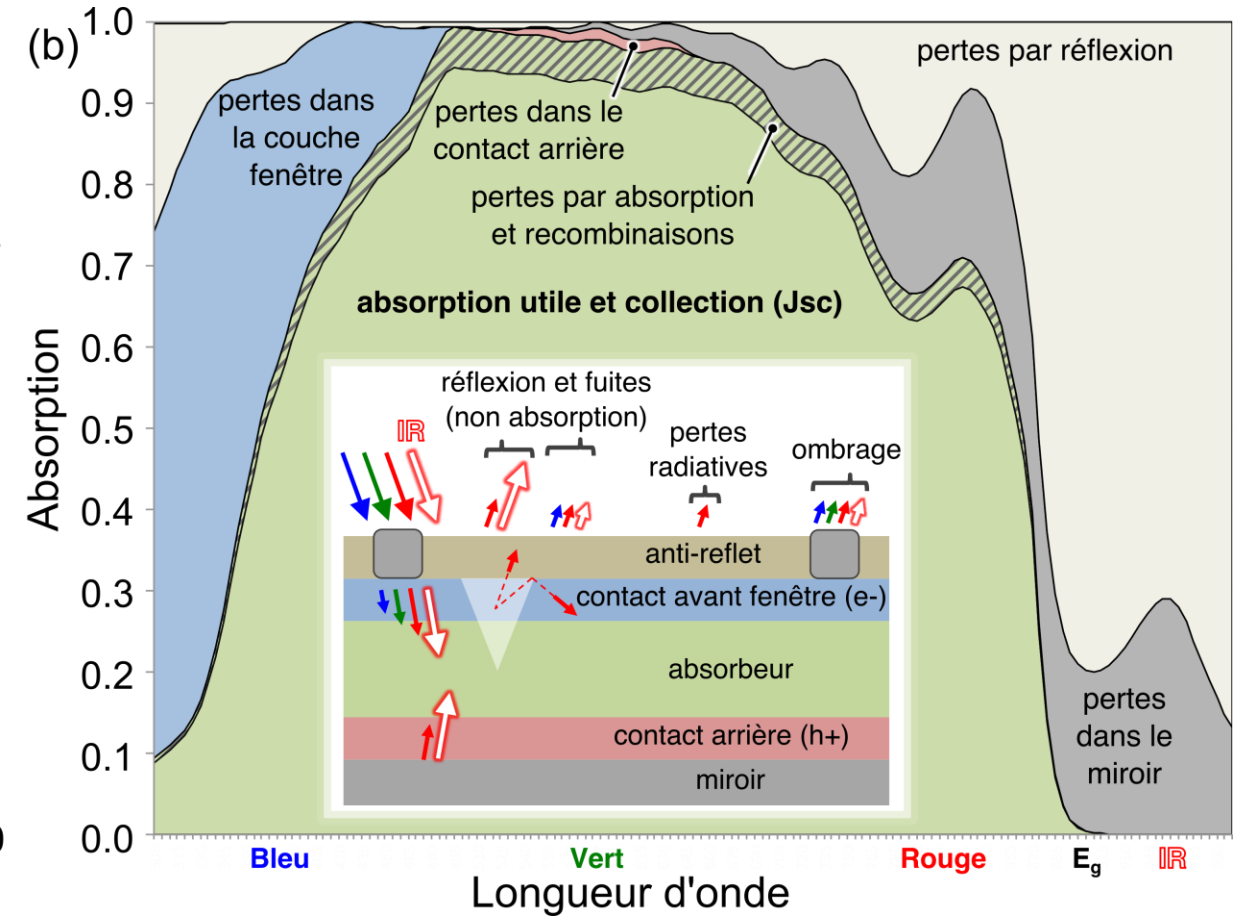
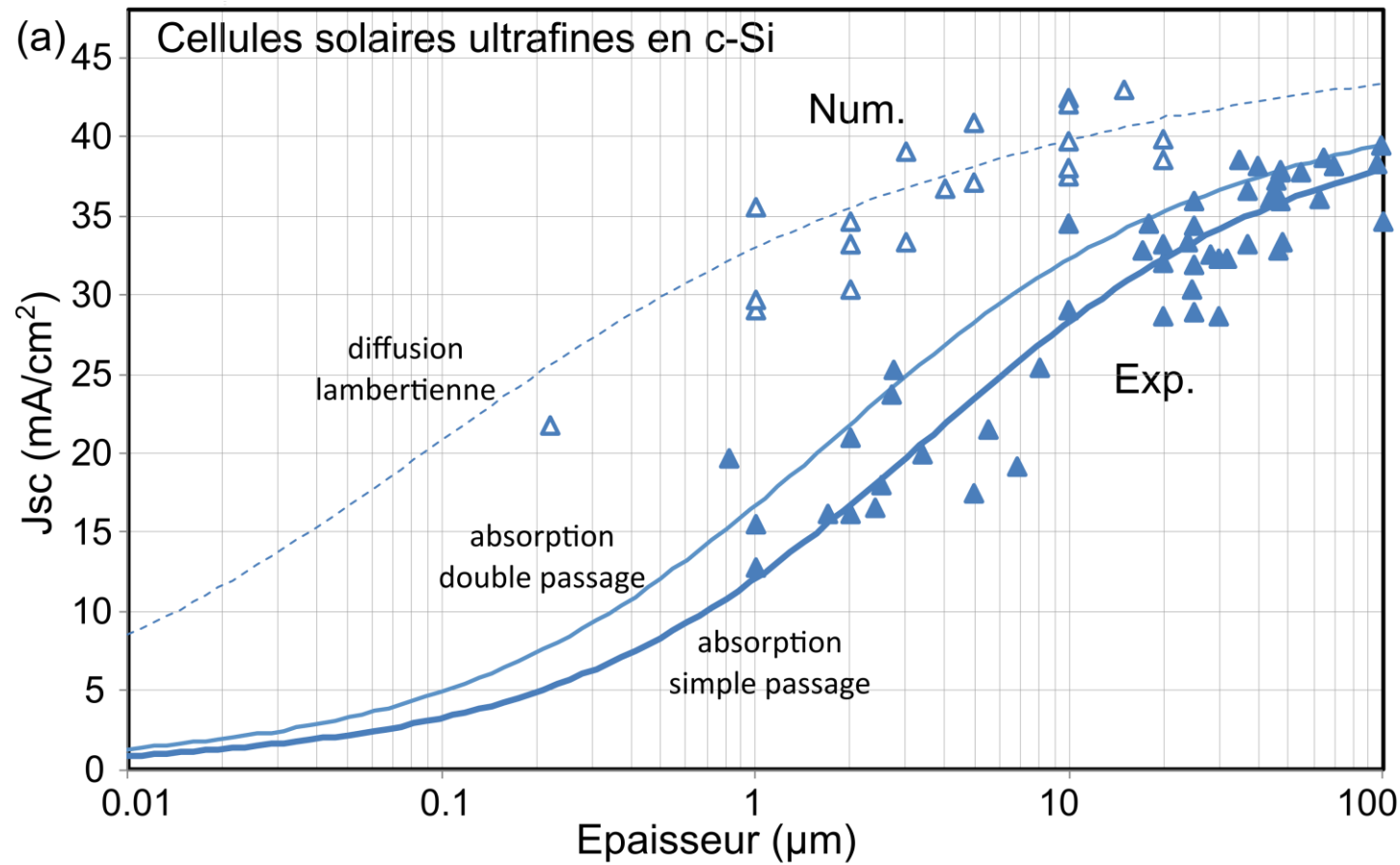
M. Giteau et al, World Conference on Photovoltaic Energy Conversion (WCPEC-7) 2018



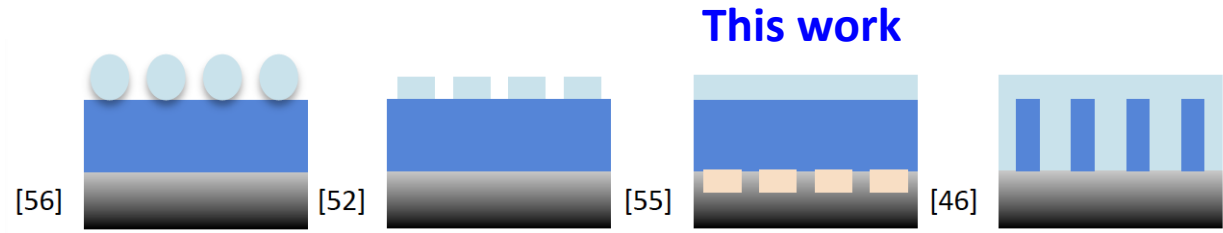
Exemple Si

Les cellules solaires ultrafines, Stéphane Collin et Andrea Cattoni

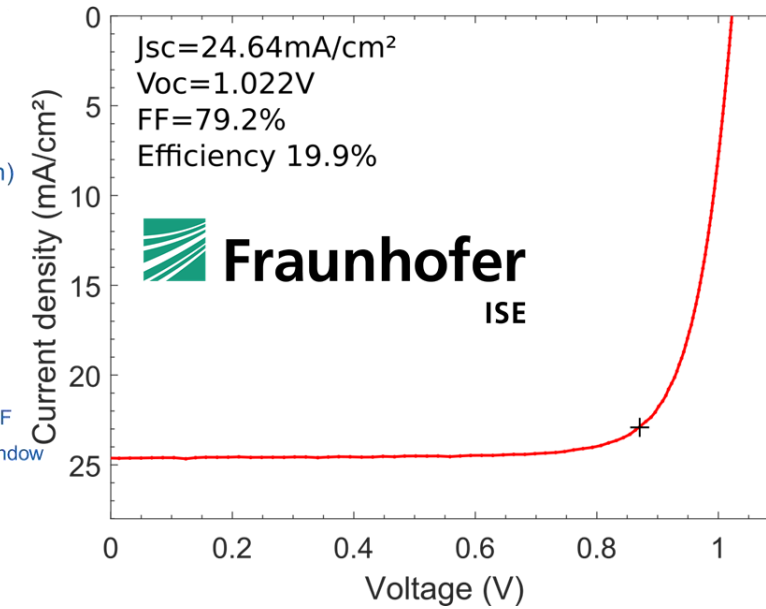
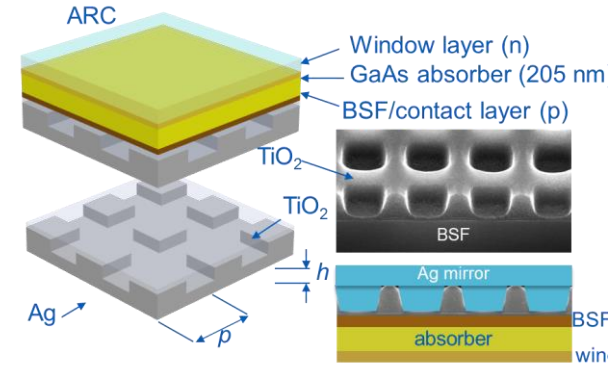
<https://doi.org/10.1051/photon/202010244>



Exemple : GaAs



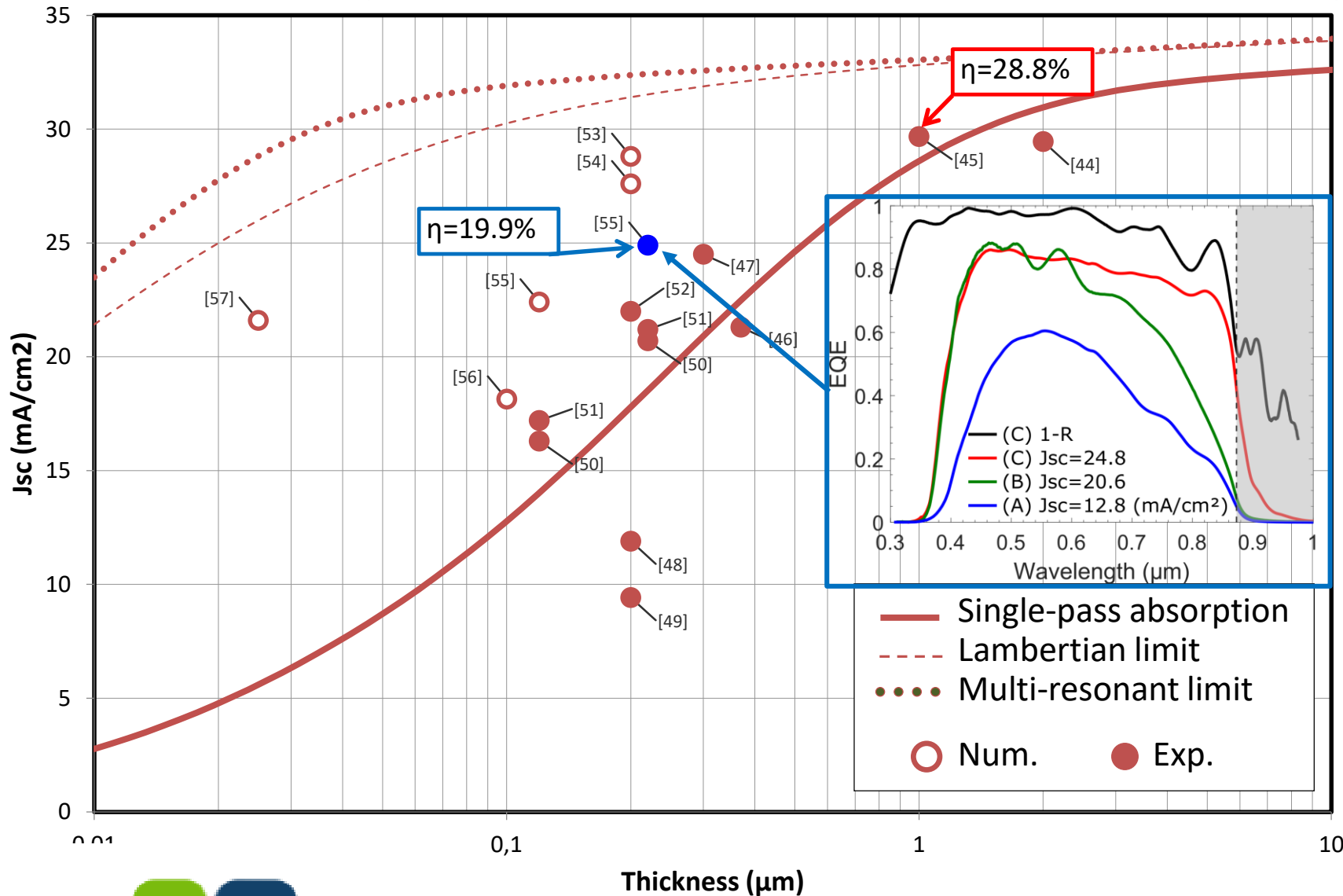
This work



Hung-Ling Chen, Andrea Cattoni, Romaric de Lépinau, et al..
A 19.9%-efficient ultrathin solar cell based on a 205-nm-thick GaAs absorber and a silver nanostructured back mirror. Nature Energy, 2019

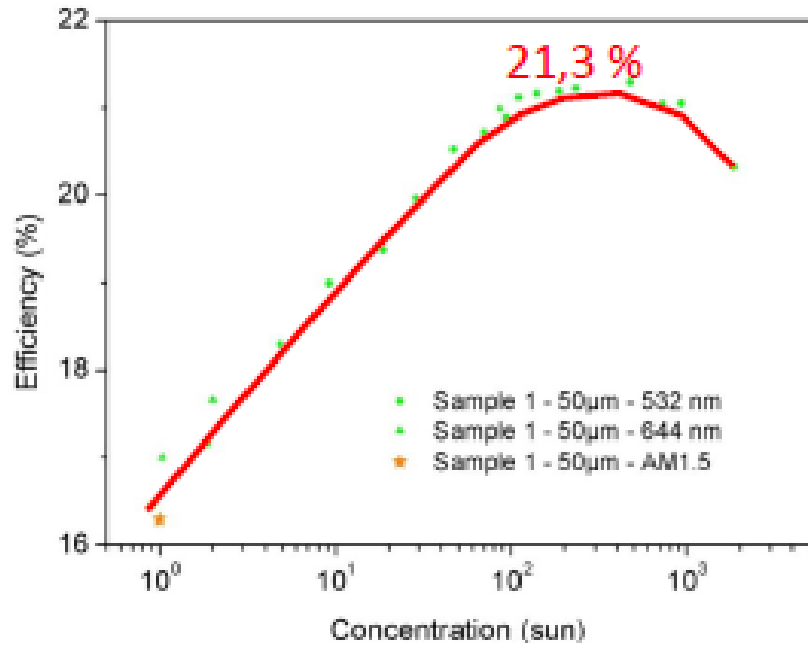
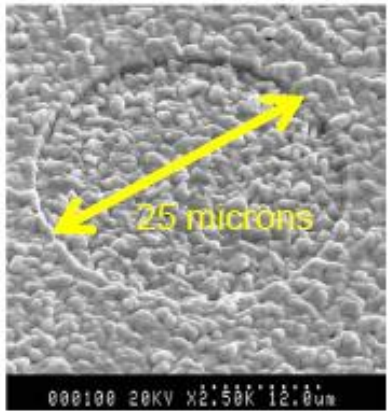
Technologie proche de la limite théorique en rendement (33%), mais loin de la limite d'absorption:

=> Cellules 10x plus fines possibles



Massiot, Cattoni, Collin "Ultrathin solar cells: recent advances, promises and challenges" Nat. Energy 2020

Concentration



Limite concentration: 46 500 fois

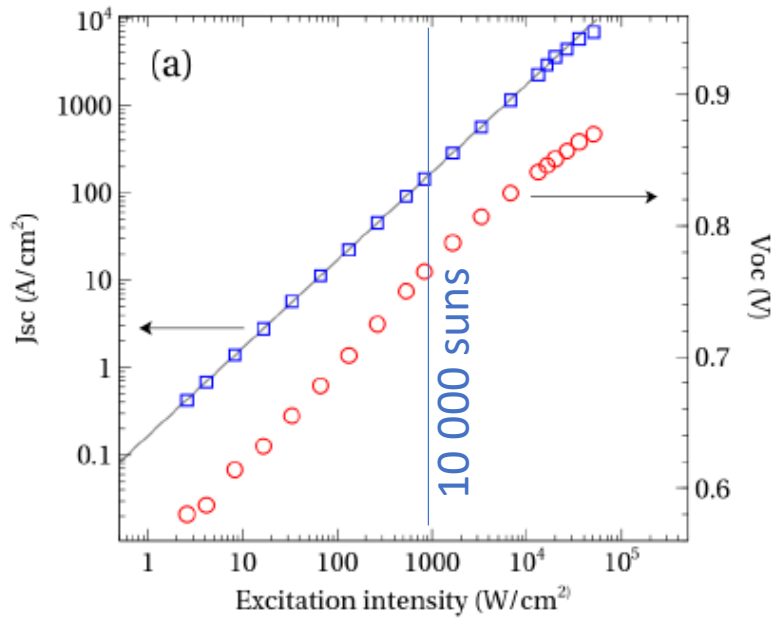
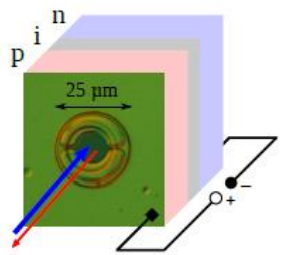
Triple problème de transport: $V = \Delta E_f \sim \log(p.n)$

- Photons
- Electrons
- Chaleur

⇒ Pic de rendement avec la concentration

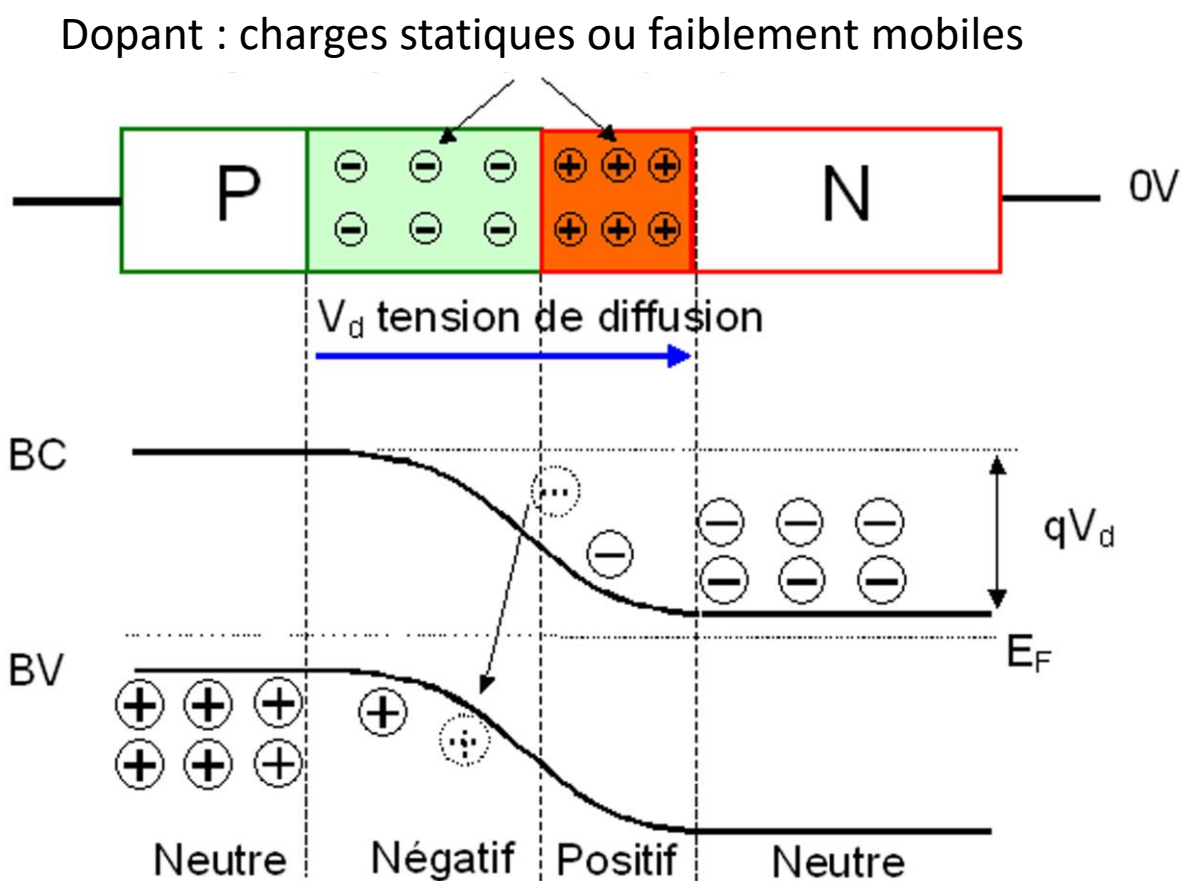
Conversion d'une puissance équivalente à 100 000 soleils

Feynman: « There is plenty of room at the bottom »



Trung Dac Nguyen et al, Nat Energy 2018

Durée de fonctionnement: quelle limite?



Les homojonctions p/n sont généralement instables [1,2]

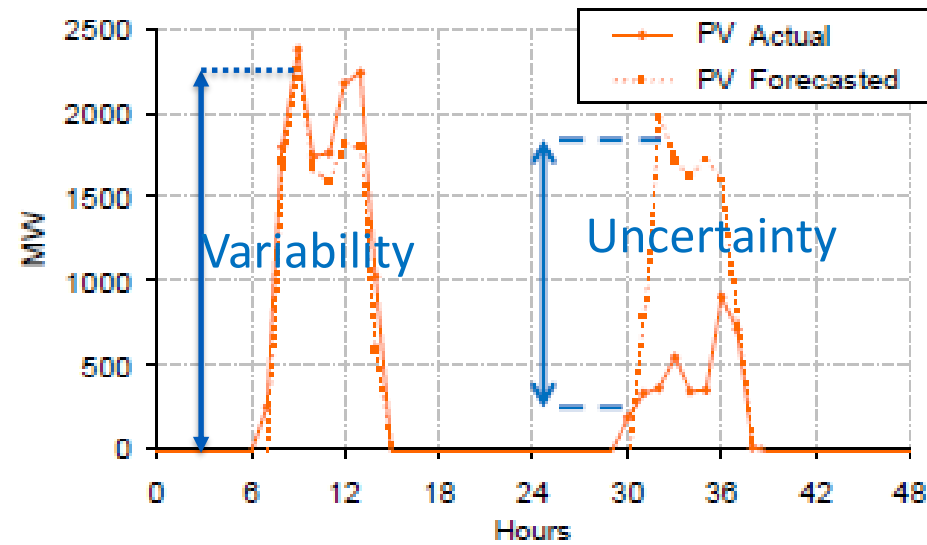
Certaines jonctions p/n peuvent être stables

C'est un domaine très largement à développer!

[1] J.-F. Guillemoles, I. Lyubomirsky, I. Riess, and D. Cahen, J. Phys. Chem. 99, 14486-14493 (1995)

[2] I. Lyubomirsky, V. Lyakhovitskaya, J.F. Guillemoles et al., J. of Crystal Growth, 161, 90-93 (1996)

Problème du facteur de charge



15% facteur de charge moyen en France

20-25% aux US (Tracking)

Et pourtant le soleil brille tout le temps...

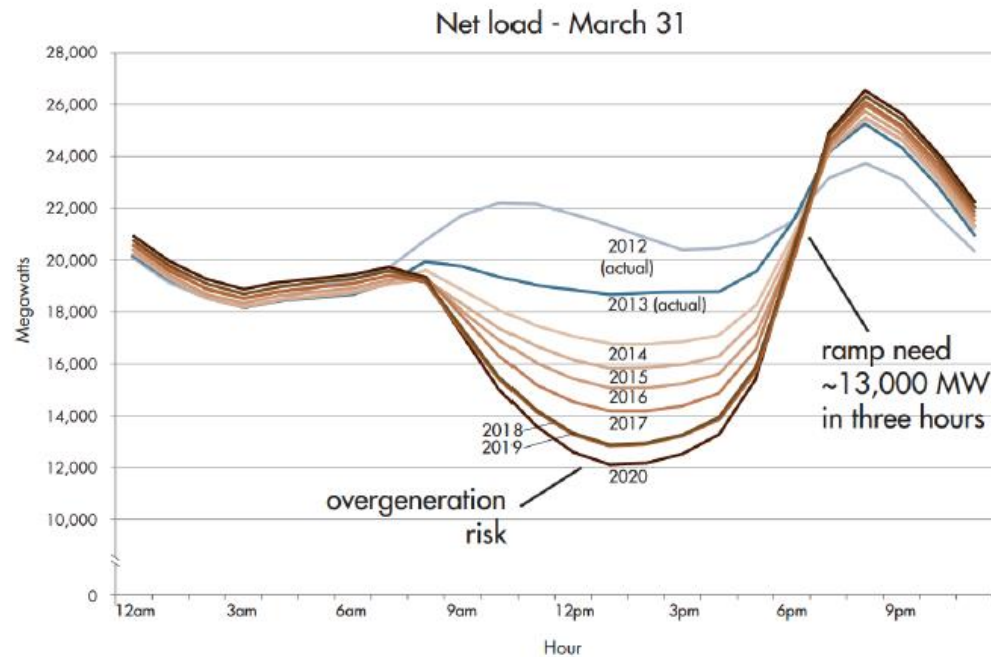
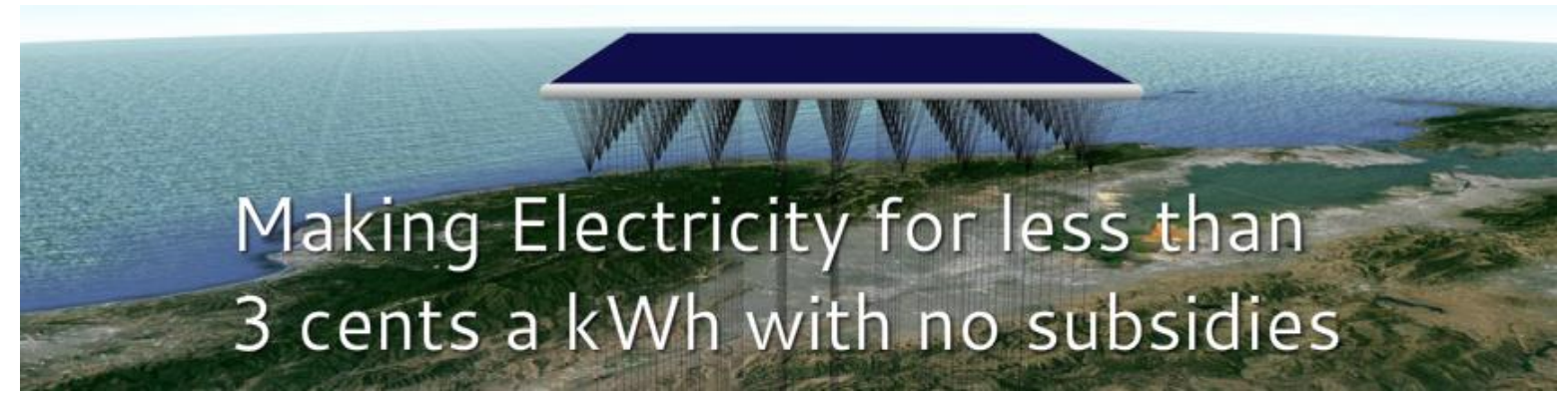
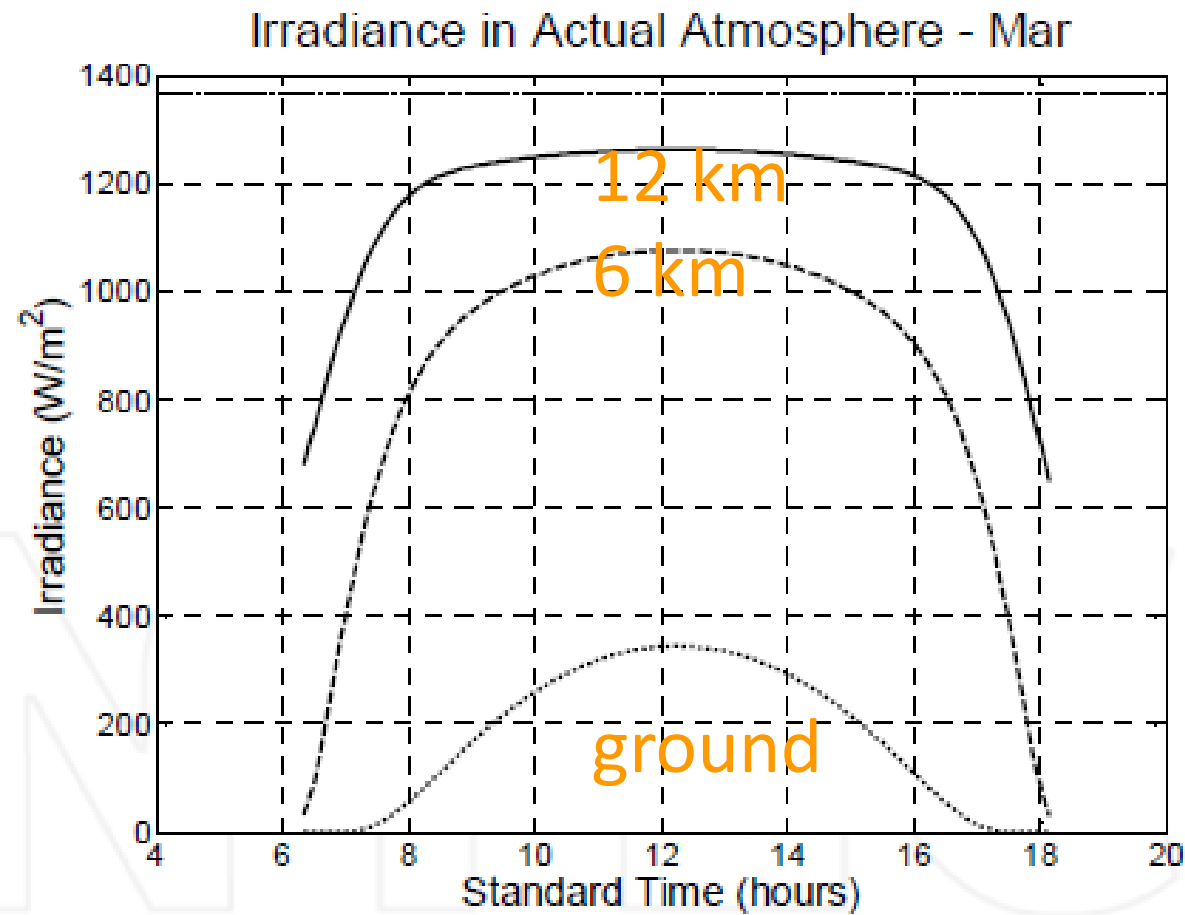


Figure 1. The CAISO duck chart

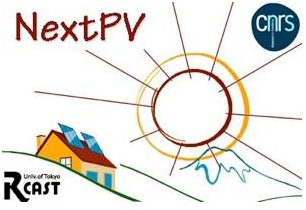
Source: CAISO 2013

Là où le soleil brille tout le temps



« There is plenty of room up there, also » (anonyme)

Exemple



35 m radius flying 6 km high

- 90 t lift
- 2.5 kg/m² (enveloppe + cells) => 46 t
- 16 t cable (Al fibers reinforced, 55 m/s winds, 5% electric losses)

- 20% cells + tracking => 0.9 MW plant with 50% capacity factor
- Cost estimates \$1/W possible
- Stores 180 000 m³ H₂, i.e. about 8 days PV production equivalent

1 Low footprint
Strongly reduced structure materials
Little competition for use of space

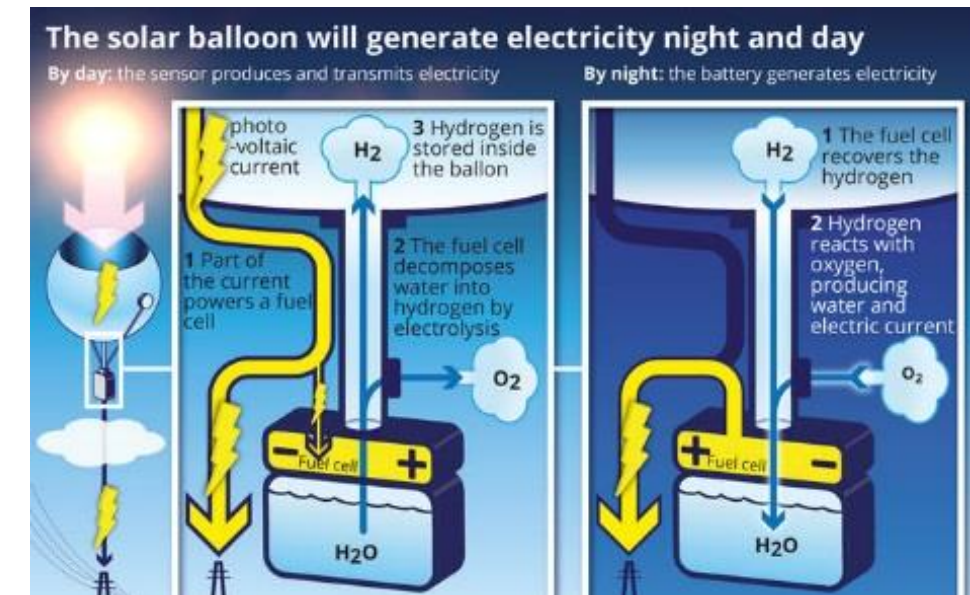
4 Energy storage
Low cost energy storage (H₂),
built-in

2 Higher productivity
Capacity factor up to 50% (above
clouds)
More incident power (+ 30%)

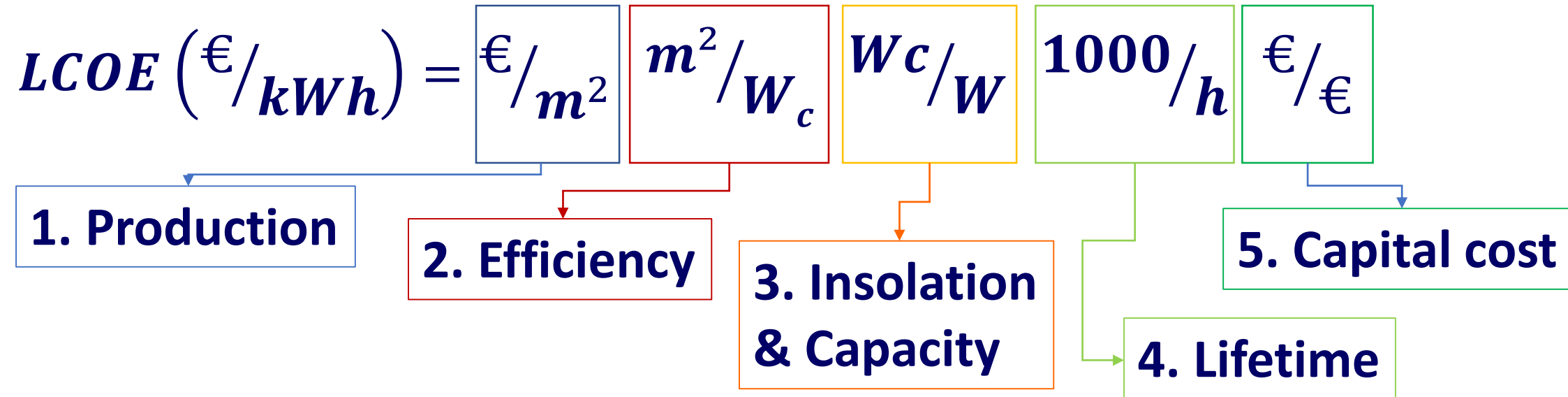
5 Deployment
Ease and rapidity of installation

**3 Higher efficiency from
concentration**
More direct insolation
Lower active material usage

6 Availability
Everywhere on earth!



Aglietti et al. 2010; Guillemoles et al. 2015



1. Innovative processes, scale up, standardization => Down to 20€/m²
2. Abs/unit volume, low defect, new concepts => Up to 66 % (one sun)
3. Localisation, tracking, ... => Up to 50% capacity factor
4. Failure mech., operation conditions => Up to 50 years
5. Interest rates, business model => Free

⇒ LCOE (modules) < 0.1 €/MWh from best values ⇒ Free energy?



Une source d'énergie:

Quasi gratuite...

Tout le temps...

A faible empreinte ...

⇒ Qu'en ferons nous?

Une énergie peut être gratuite et à faible impact à la production. Quels sont les coûts et les impacts de son utilisation?

Summary of maximal efficiencies

Type of cell (ideal)	Ideal efficiency range AM1.5 à x46000	Remarks
MJ N > 100	68-87%	Extremely complex to implement
Hot carriers	67-86%	Proof of concept, 11% achieved
Impact ionisation (multiples Eg)	44-86%	Proof of concept, 5% achieved
Thermoionique, thermal, TPV	54-85%	23% achieved
Intermediate bands (N>10)	62-85%	Extremely complex
MJ N=3	49-64%	39%-47% achieved
Up conversion	48-63%	Small gain achieved
Intermediate bands (N=1)	48-63%	Proofs of concept/ Small gain
Tandem N=2	43-56%	32% achieved
Down conversion	39-52%	Proofs of concept/ Small gain
Impact ionisation (2 Eg)	38-52%	5% achieved
Rectennas	?-48%	Proof of concept
Junction p/n , single	31-41%	28% -29% achieved

Useful reading

- **P.T. Landsberg 1978**

Thermodynamics and statistical mechanics, P.T Landsberg, Dover, 1978
Nice chapter on blackbody radiation

- **A. De Vos 1992**

Thermodynamics of Solar Energy Conversion, Alexis De Vos, Wiley-VCH, 1992
General but easy on solar energy conversion

- **MA Green 2003**

Third generation photovoltaics, M.A. Green, Springer, 2003
Short but rather complete on the bases of advanced photovoltaics

- **P. Würfel 2005**

Physics of Solar Cells, Peter Würfel, Wiley-VCH, 2005
Excellent physical exposition of the bases of photovoltaics

- **JM Rax 2014**

Physique de la conversion d'énergie, Jean-Marcel Rax, EDP Sciences/CNRS Editions, 2014
Direct energy conversion, revisited