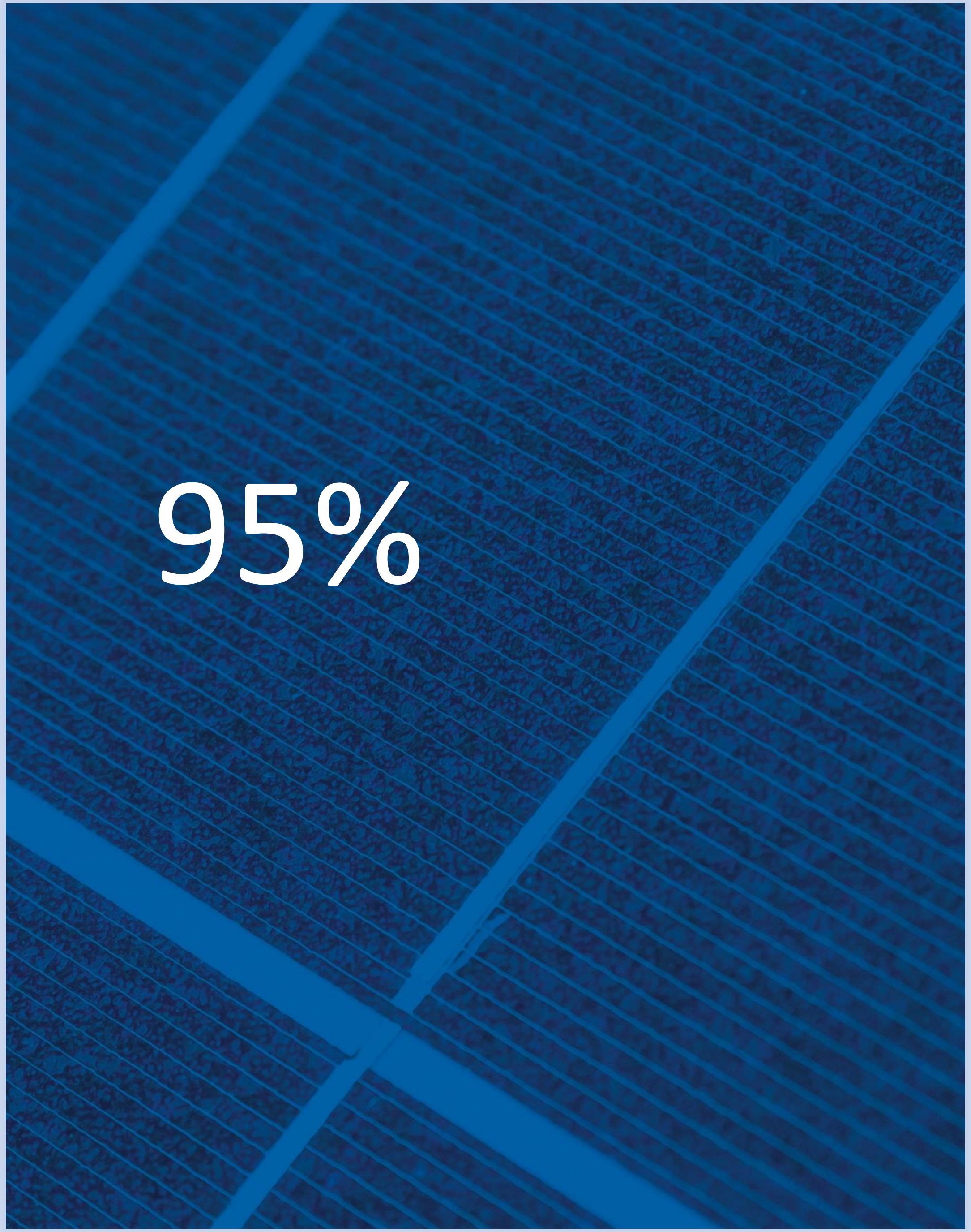
Photovoltaïque, approches « exotiques »

Jean-François GUILLEMOLES, Rodolphe VAILLON, David DUCHE, Frederic SAUVAGE, James CONNOLLY, Stefania CACOVITCH, Daniel LINCOT, Daniel SUCHET, Nicolas BARREAU, Negar NAGHAVI, Pere ROCA Y CABAROCAS, Thomas FIX, Abdou SLAOUI, Aline NONAT, ...

UMR IPVF, IES, IM2NP, LRCS, GEEPS, IMN, LPICM ....

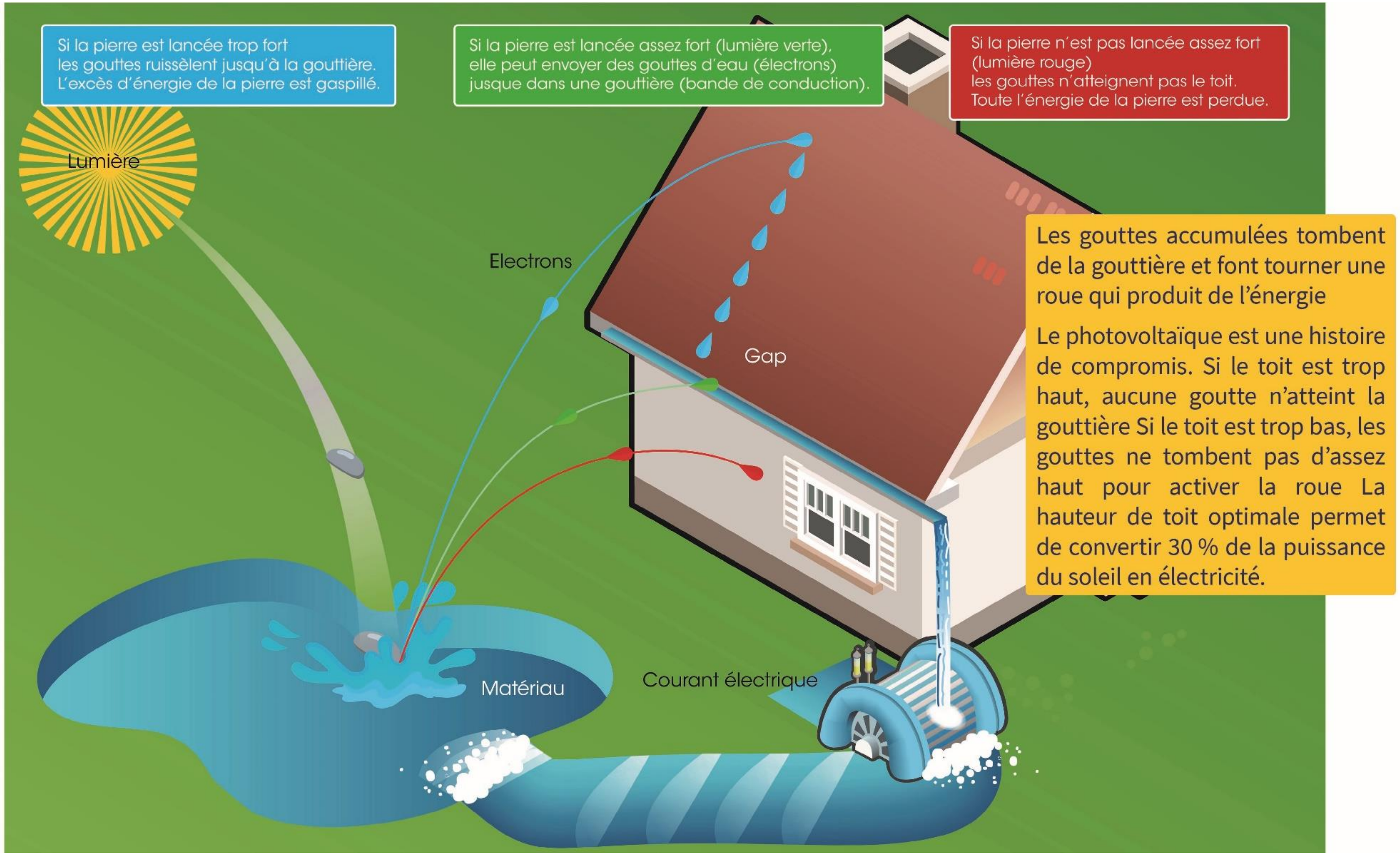
25-27 aout 2021

Le photovoltaïque « exotique »



- De quoi s'agit t-il?
- Pourquoi faire?
  - Répondre aux défis du PV (efficacité, soutenabilité, usages, …)
  - Curiosité
- Ex: efficacité
  - Energie diluée spatialement, spectralement, angulairement, incohérente, …

Quantum physics made easy



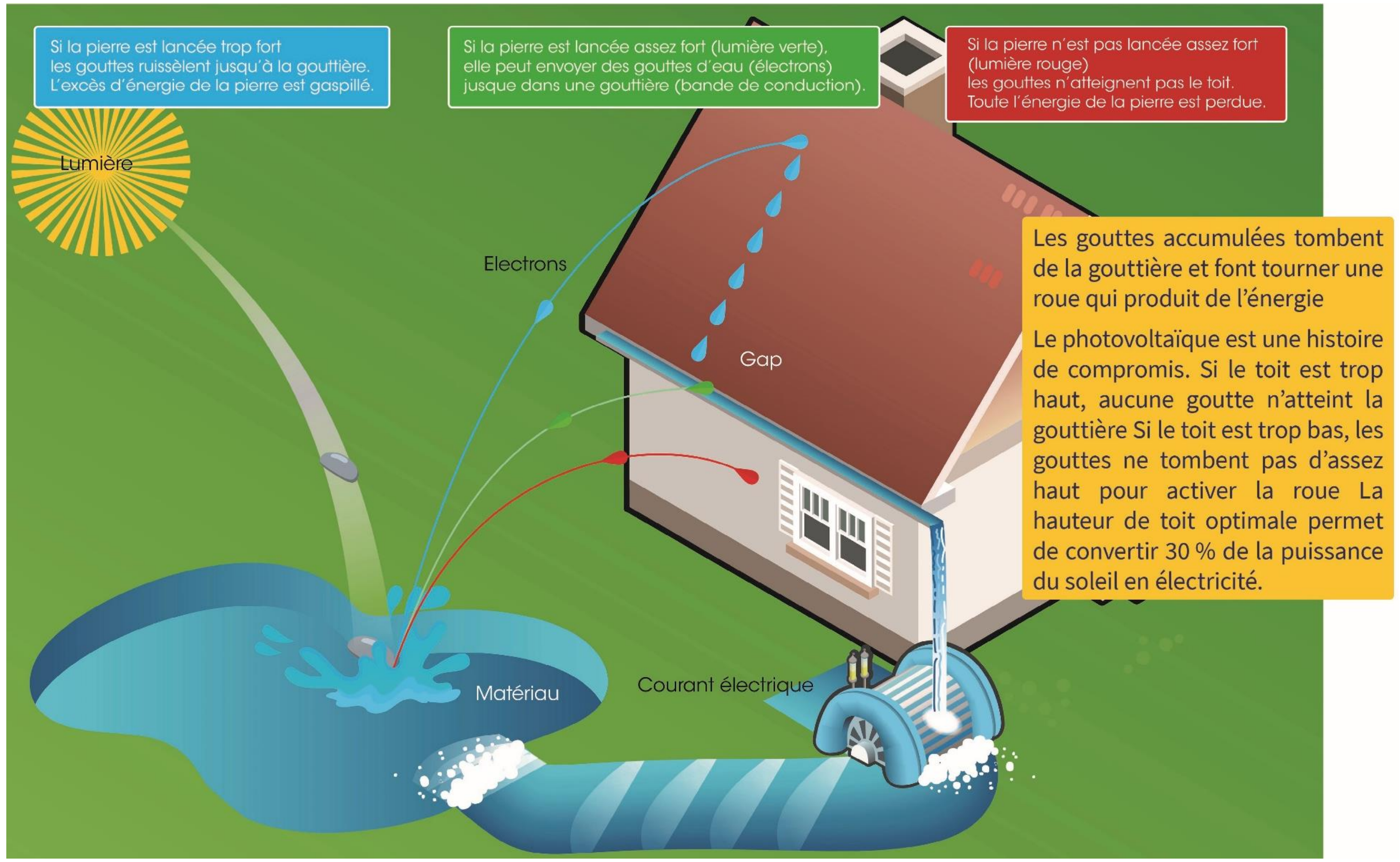
Guide for the perplexed to the Shockley–Queisser model for solar cells

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

Nature Photonics **13**, 501–505 (2019) | Cite this article

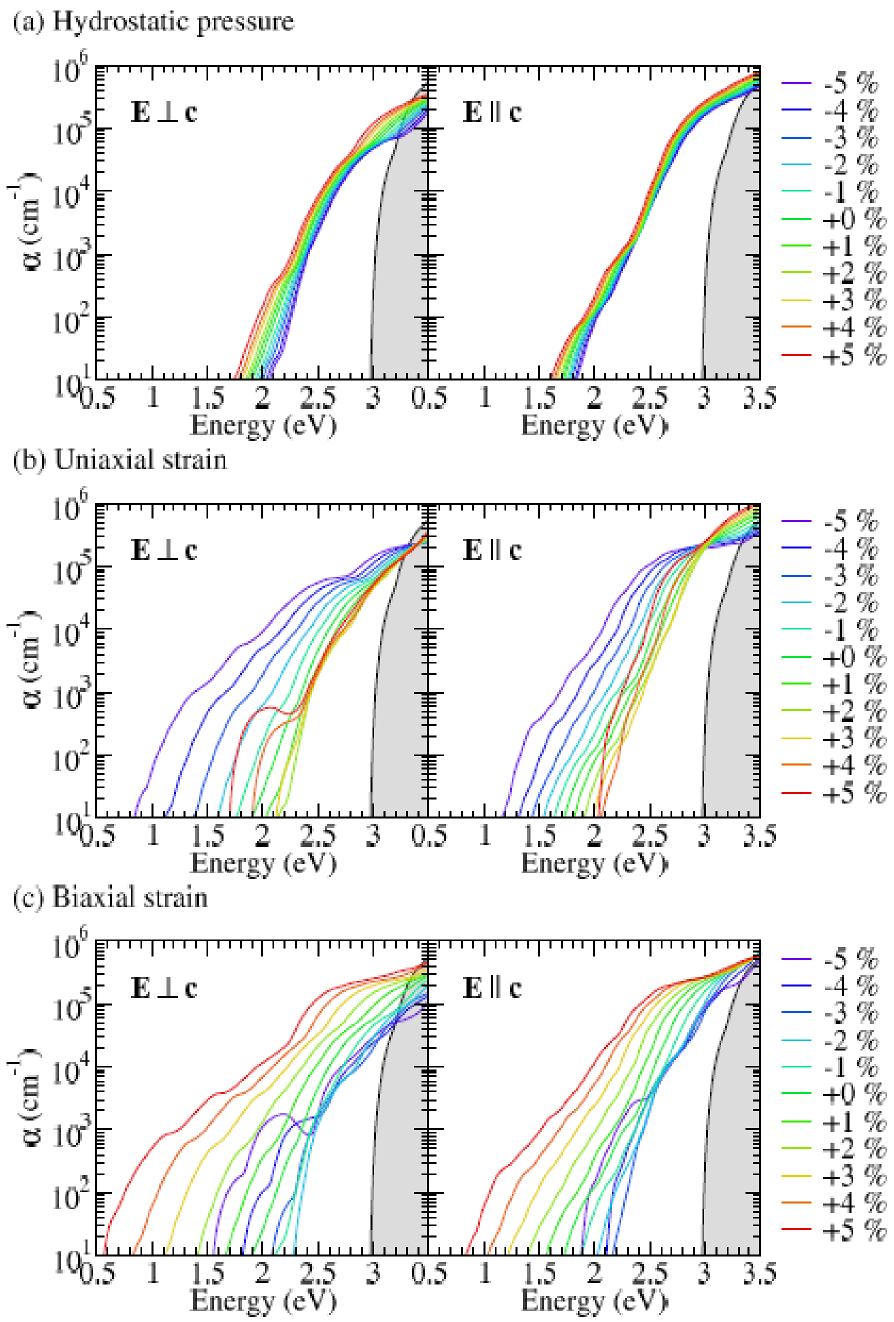
IPVF UMR 9006 Joint Research Unit

Le photovoltaïque « exotique »



- Peut-on améliorer le système existant?
  - Nouveaux Matériaux
  - Nouveaux Procédés
  - Nouveaux Dispositifs
- Peut-on l'utiliser pour d'autres applications?

Nouveaux Matériaux



DOI: 10.1103/PhysRevB.92.045207

1. Le silicium à gap direct (IPVF, LPICM, Icube)

Si hexagonal sous contrainte postulé (IRDEP 2015), Synthétisé (LPICM 2018), Emission alliages SiGe 2020 à 4K (https://www.nature.com/articles/s41586-020-2150-y)

Chlatrates de Si (ICUBE: gap 1.7 eV, premières cellules PV , https://pubs.acs.org/doi/10.1021/acs.jpcc.0c02712)

2. Nanomateriaux : QD, NW (C2N, LPICM, NEXTPV, …)

Nanofils de Si => PV ultra léger; Adaptation du seuil d'absorption

Voir aussi S. Collin

2. Ferroélectriques (ICUBE)

Champs électriques internes comme alternative aux jonctions p/n pour extraire les charges (Voc ~ 4V> gap 1,5 V pour Bi_2FeCrO_6 ; ICUBE https://pubs.acs.org/doi/10.1021/acsaem.9b01465)

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Clathrates de silicium

Diamond silicon:

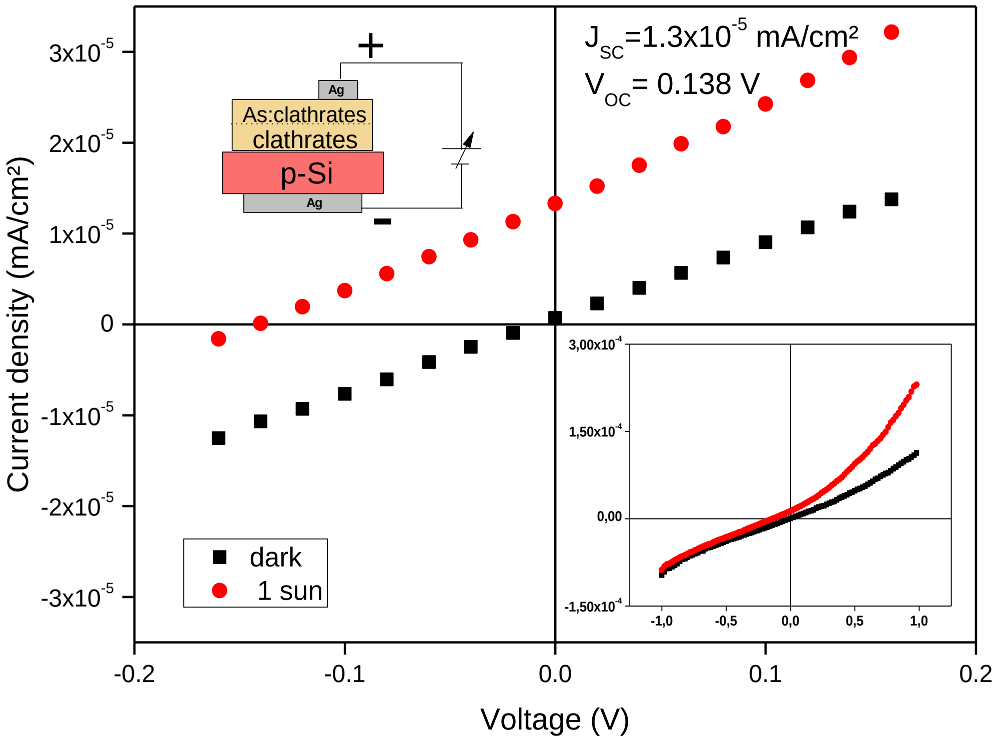
2^{nd} most abundant element (26%)
Main drawback: Indirect bandgap

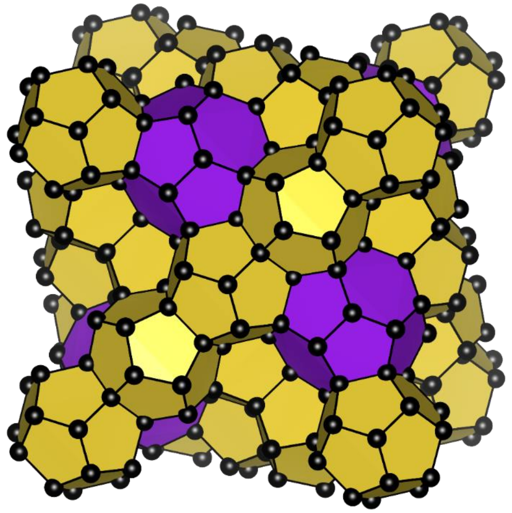
Can we do better with exotic silicon?

Type II silicon clathrates Na_xSi_{136}:

24 cages (16 Si_{20} and 8 Si_{28}) per unit cell
Guest atom inside with variable concentration
High absorption coefficient
1.8 eV direct bandgap for low Na content

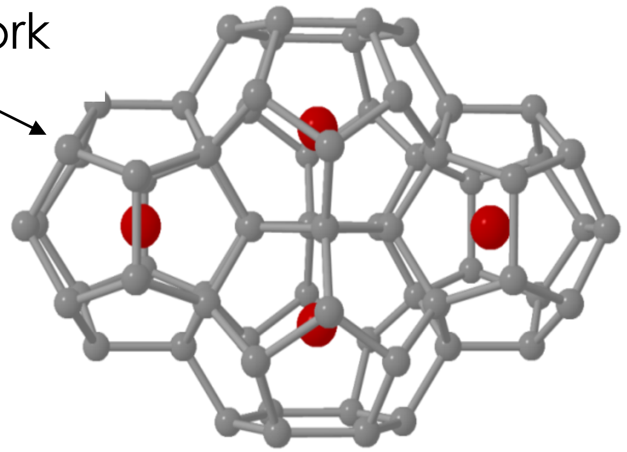
T. Fix, R. Vollondat, et al., J. Phys. Chem. C ***124****, 14972 (2020)*





Si framework

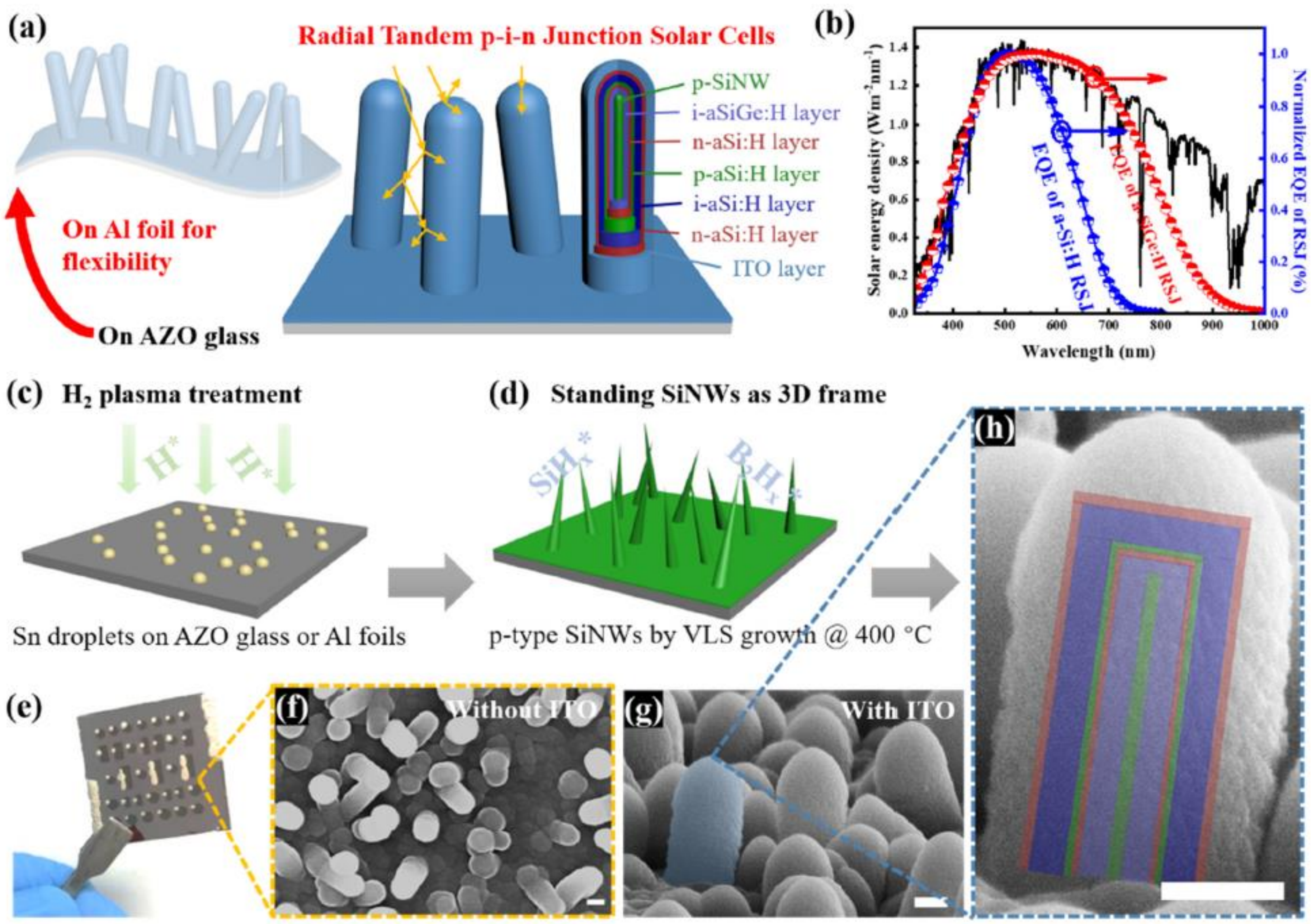
Guest



Thomas FIX

	Undoped Clathrates	Arsenide-doped Clathrates (dose (at/cm²))		
		1.00E+15	5.00E+15	1.00E+16
V_{OC} (KP) [mV]	19±4	40±3	98±7	142±8
V_{OC} (Solar Simulator) [mV]	39±6	59±5	138±10	203±10

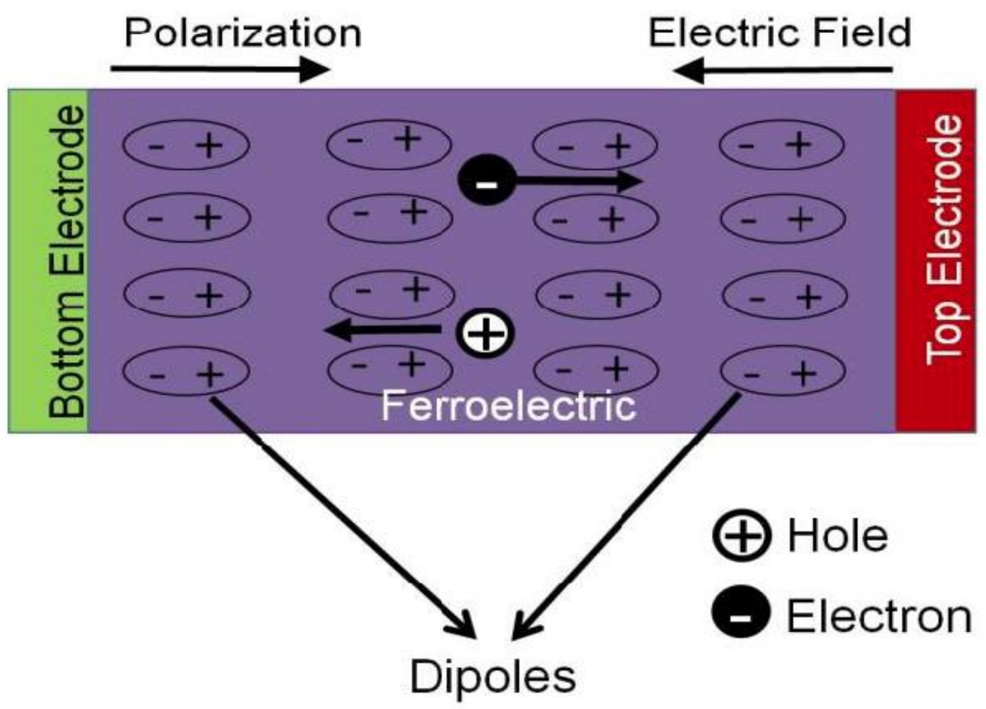
Highly Flexible Tandem RJ Solar Cells with excellent power-to-weight ratio (LPICM)

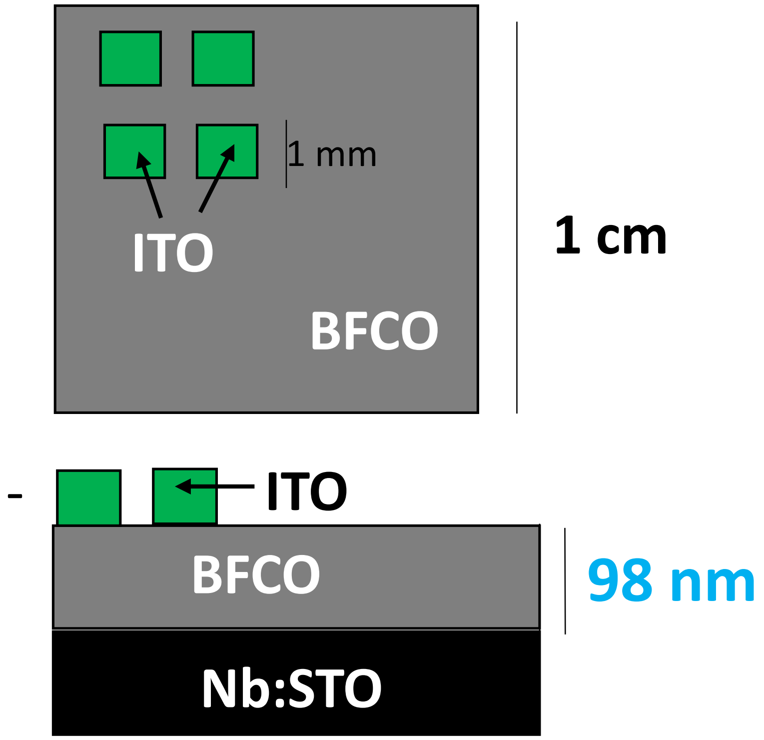


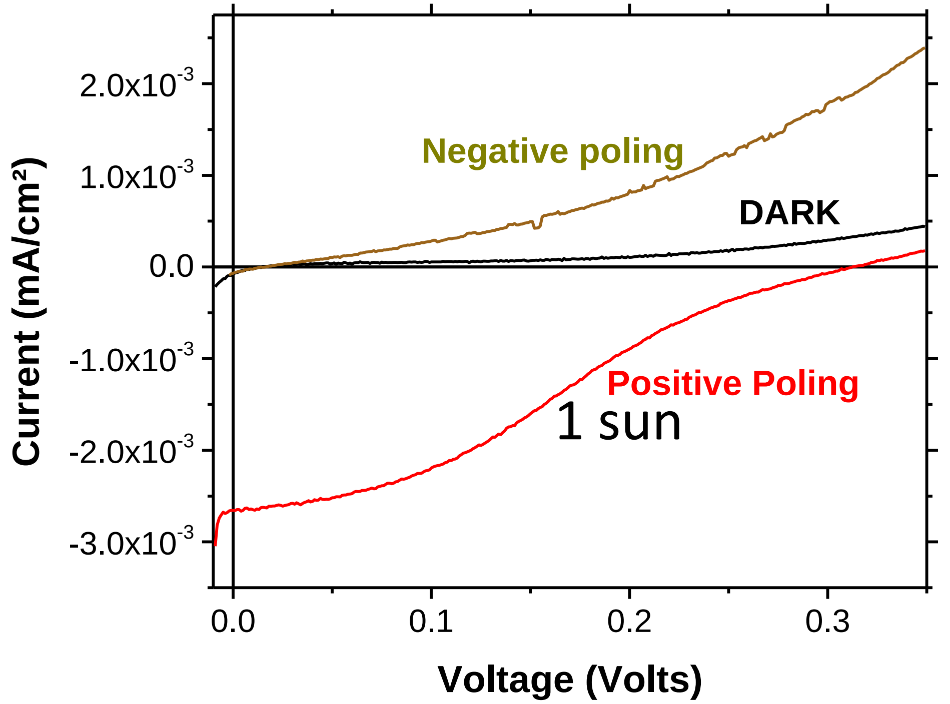
- Procédé PECVD à basse température
- Simplicité "one pump-down process"
- Cellule tandem à jonction radiale
- Substrat flexible: Feuille Al 25 µm
- **1628 W/kg**

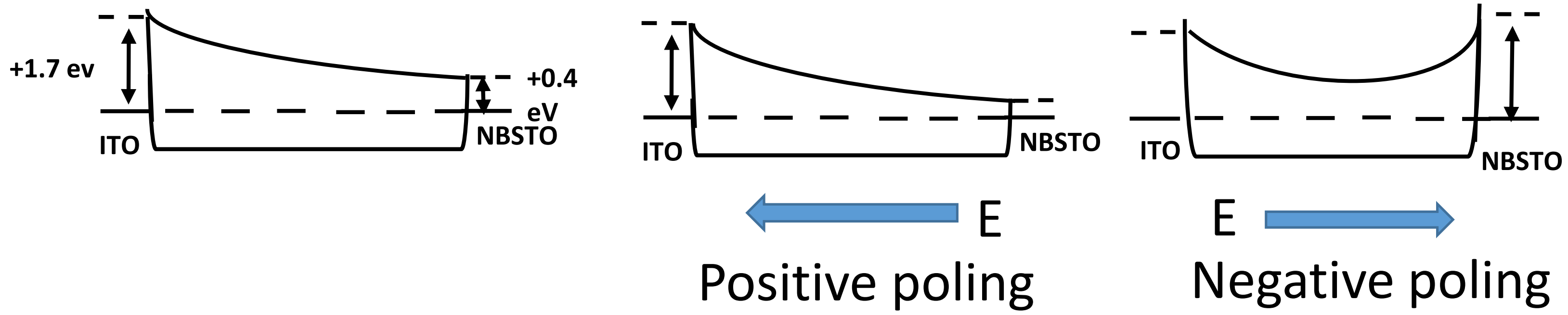
Nano Energy doi.org/10.1016/j.nanoen.2021.106121
Collaboration LPICM/Nanjing University

Role of ferroelectricity in Bi_2FeCrO_6



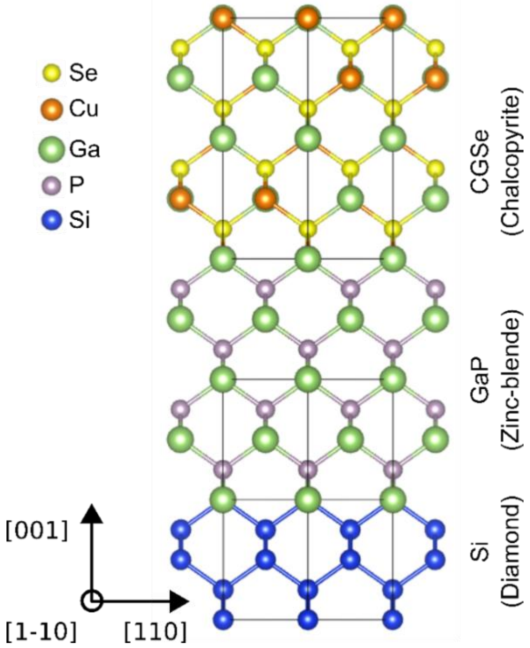


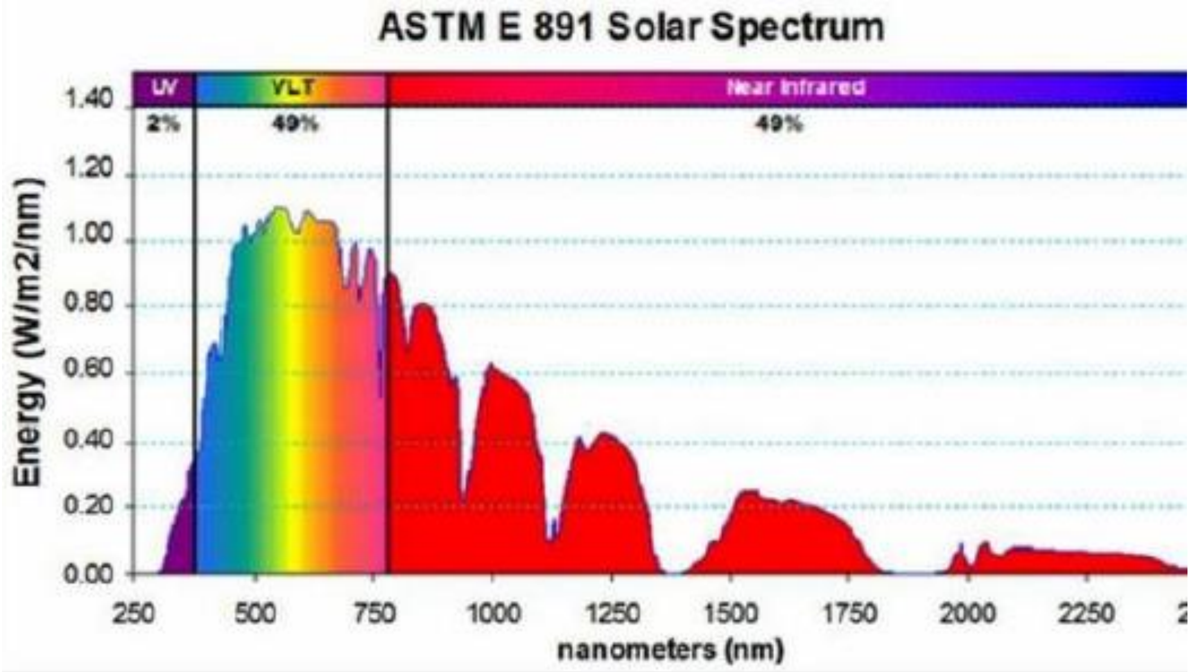




*A.Quattropani et al., Nanoscale **10**, 13761 (2018)*

Nouveaux Tandems



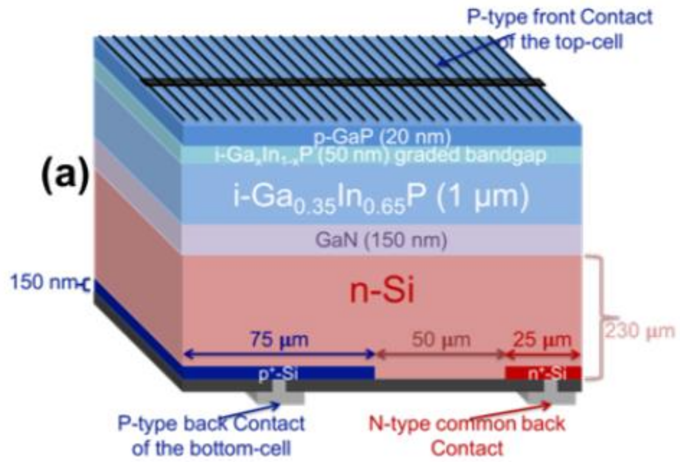


1. Tandem Chalcogénures (IMN, IPVF, FOTON, C2N, LPICM, Icube)

Tandems CIGS/PSC (Percistand)

Tandems CIGS/Si (ANR EPCIS)

Tandems III-V/Si (ANR Impetus)



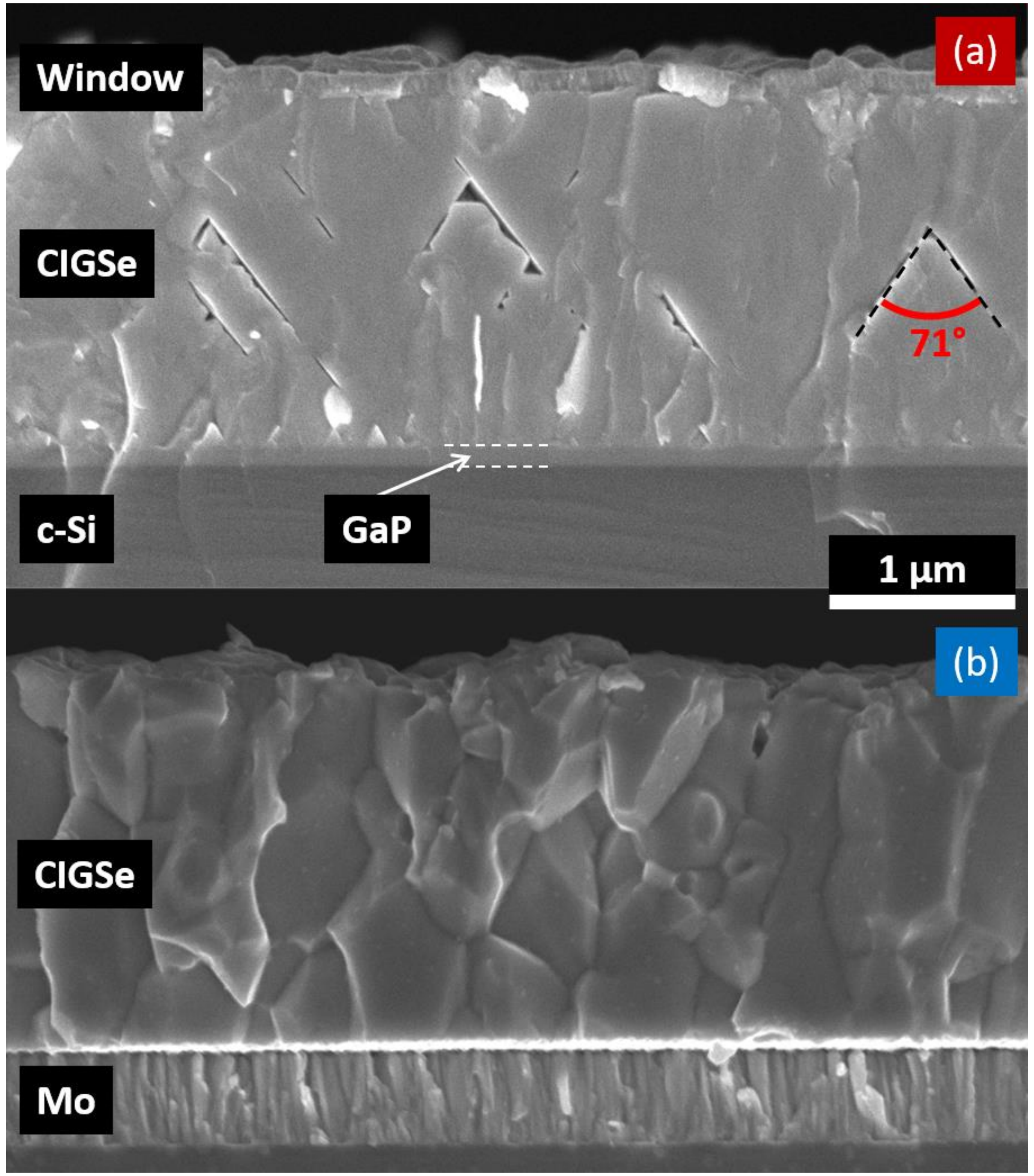
2. Tandems 3T (GEEPS)

Cellule à 3 terminaux (https://onlinelibrary.wiley.com/doi/10.1002/pip.3096) pour une meilleure adaptation spectrale

3. Tandems transparents (IPVF, LRCS)

Cellules tandems pour application dans les vitrages PV (CItySolar)

Characterization of c-Si/GaP/$CuIn_{\delta}Ga_{1-\delta}Se_2$



SEM cross sections

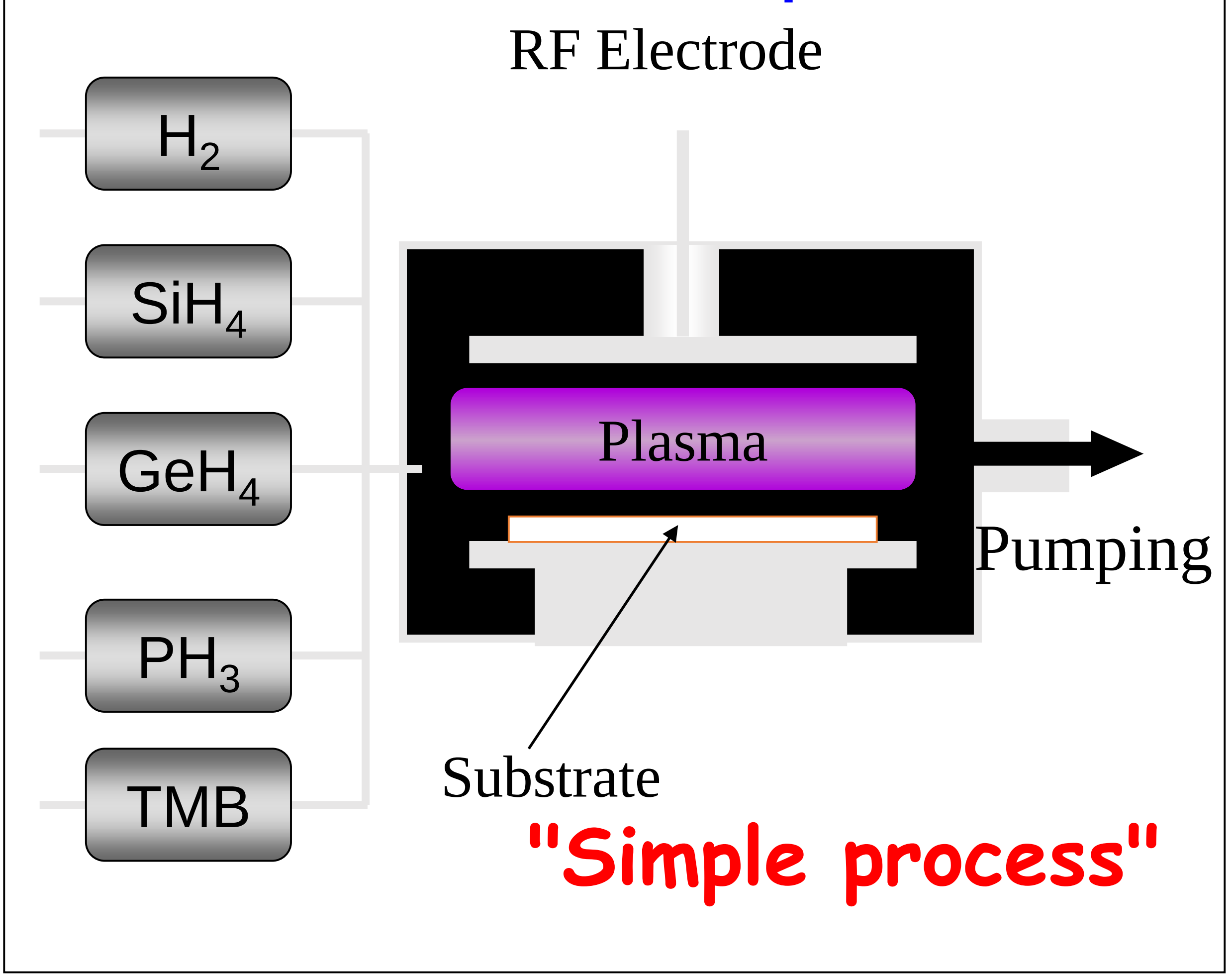
Much larger grains but specific features forming 71° angle… on c-Si/GaP

Typical polycrystalline structure on SLG/Mo

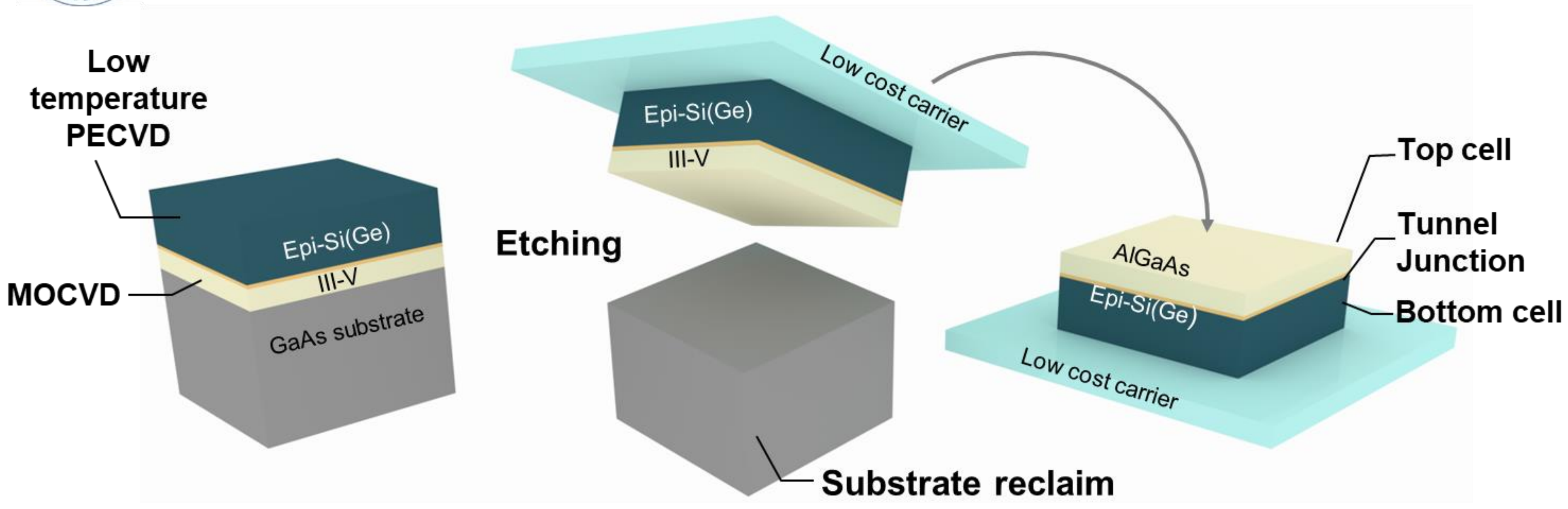
Questions :

- **Epitaxy ?**
- **What are the extended defects ?**

PECVD epitaxy of Si on III-V & Towards III-V epi-PECVD



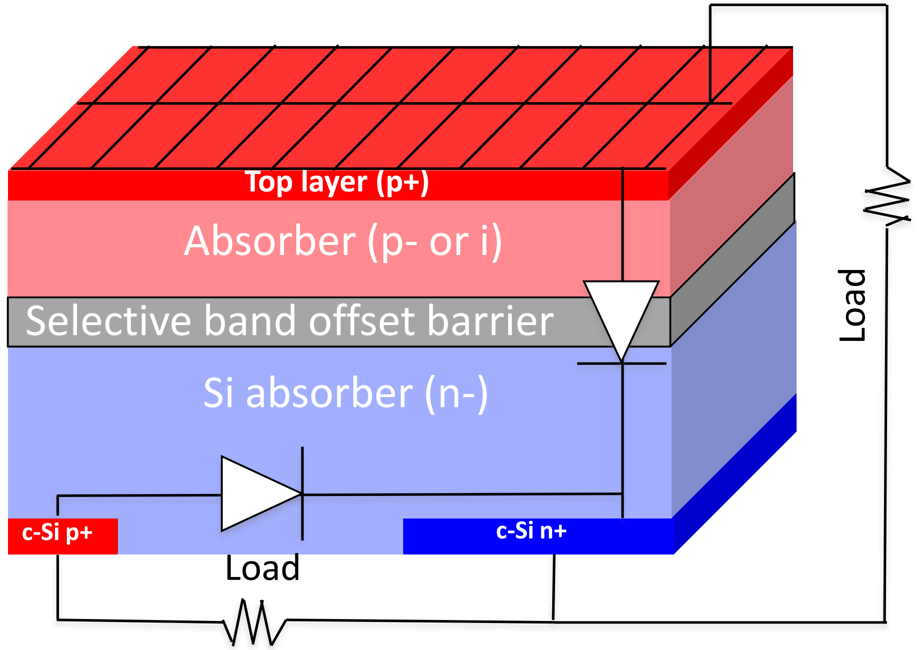
IMPETUS project

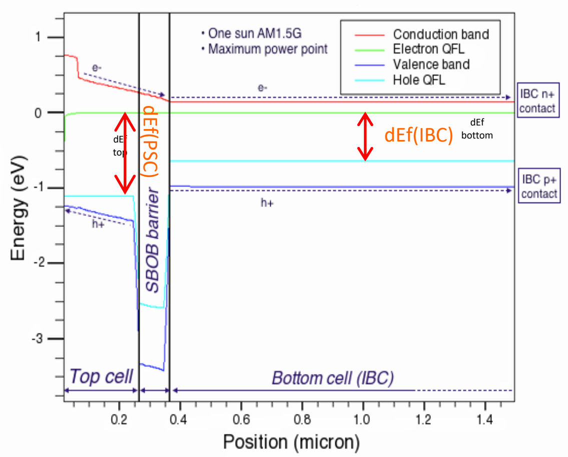


- Projet ANR IMPETUS: c-Si sur GaAs
- Epitaxie de Si, Ge, intrinsèque ou dopé
- Jonctions abruptes, jonctions tunnel

- Programme III de l'IPVF
- **Epitaxie bas cout de matériaux III-V par PVD et PECVD**

Selective band offset barrier (3T) tandems

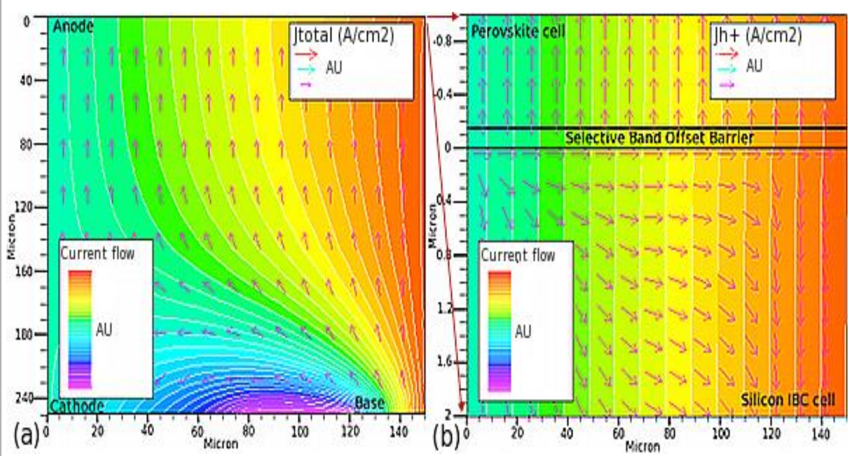




(1) Band offset barrier:

=> Separate dEf quasi-Fermi levels

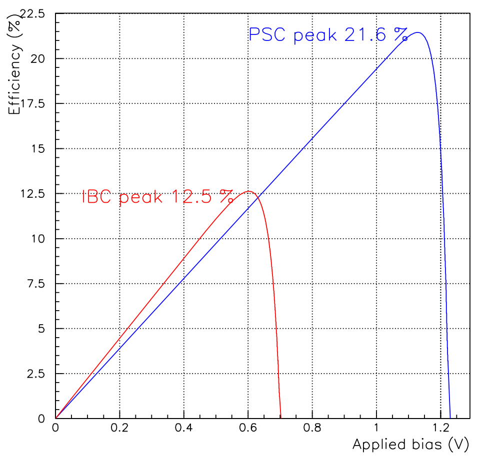
=> 3T structure, tandem efficiencies



(2) Current flows :

(a) Total current in the whole device

(b) Zoom on the interfacial hole current showing BOB in action



(3) Power : Efficiencies

Si IBC : 12.5% PSC : 21.6%

3T efficiency : 34.1%

- The Selective Barrier Band Offset Barrier Tandem : 3T-SBOB
- Recent patented at the GeePs laboratory[1]

- Two current projects at GeePs : https://anr.fr/Projet-ANR-18-CE05-0041 and https://bobtandem.wordpress.com

- Band offset barrier prevents equilibriation of a carrier (e.g. holes) - One carrier flows, the other is blocked :
- Efficiency : Same as a 4T or 3T cell without interface optical / electrical issues[2]

BobTandem

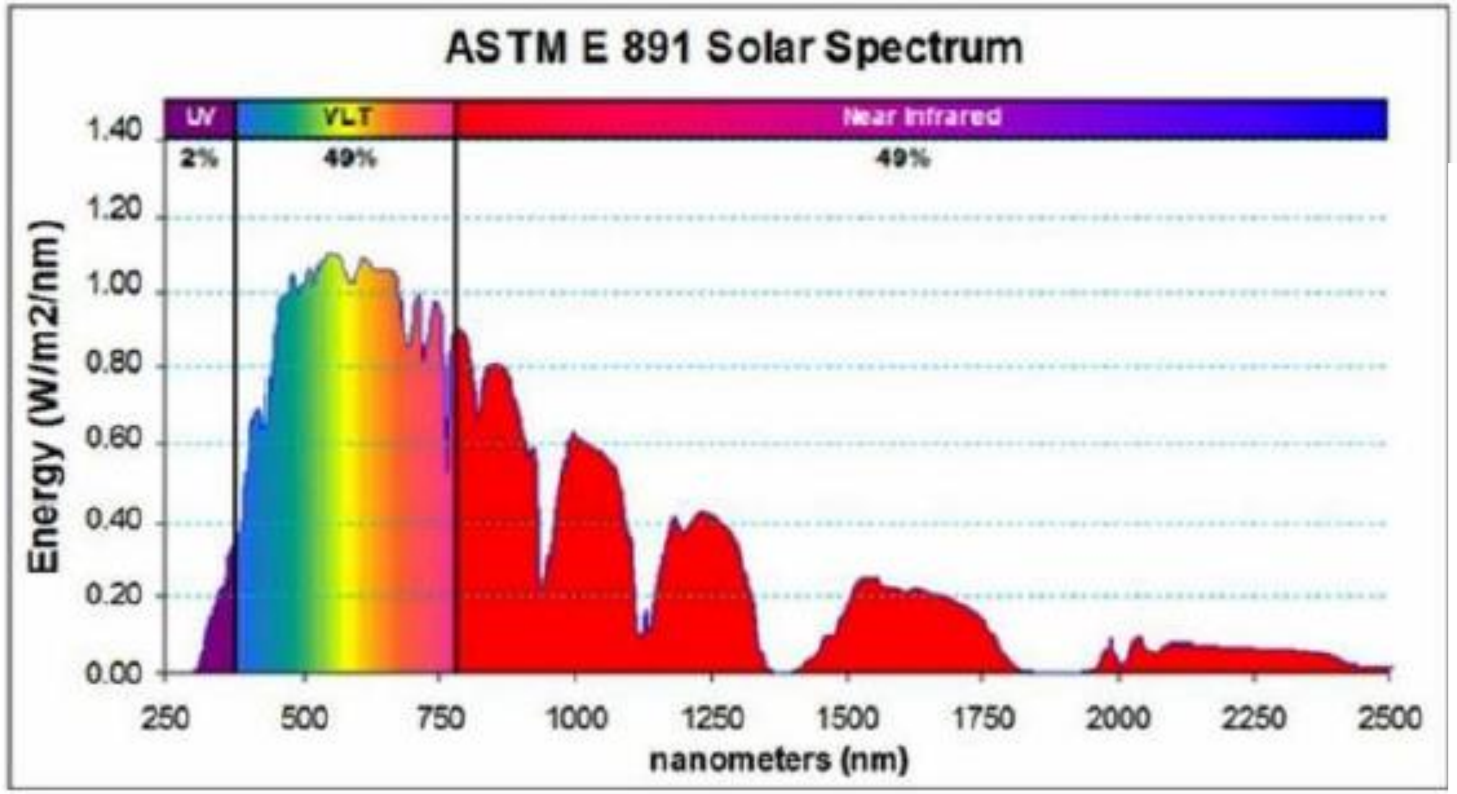
[1] Z. Djebbour, W. El-Huni, A. Migan and J-P. Kleider, Patent WO 2017/093695

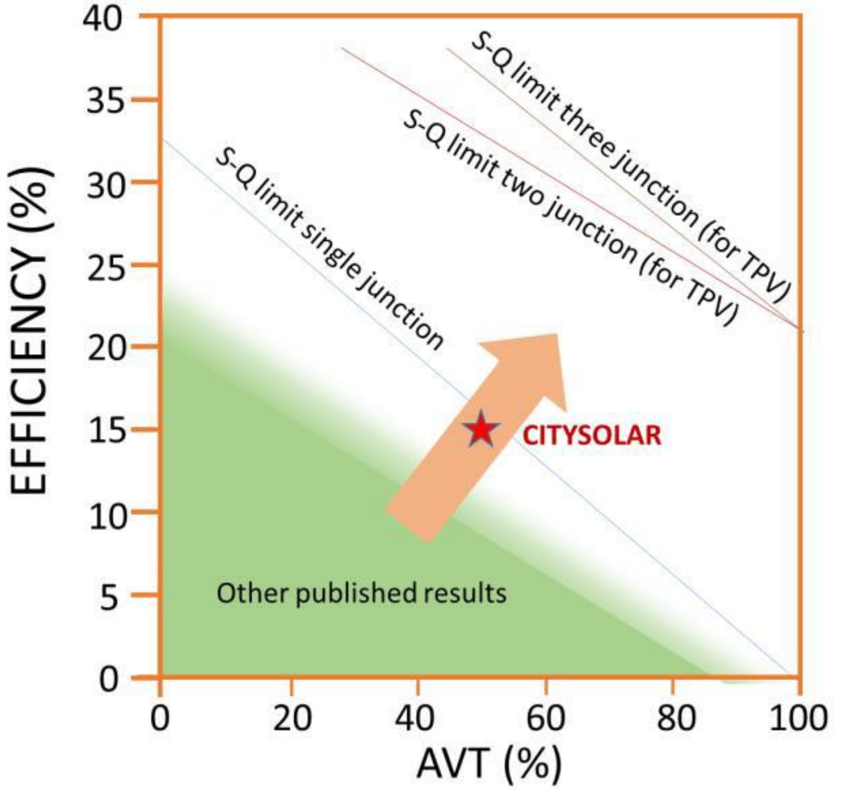
[2] J.P. Connolly *et al.*, 37th EU PVSEC, 7 to 11 September 2020, http://doi.org/10.4229/EUPVSEC20202020-1BO.16.6

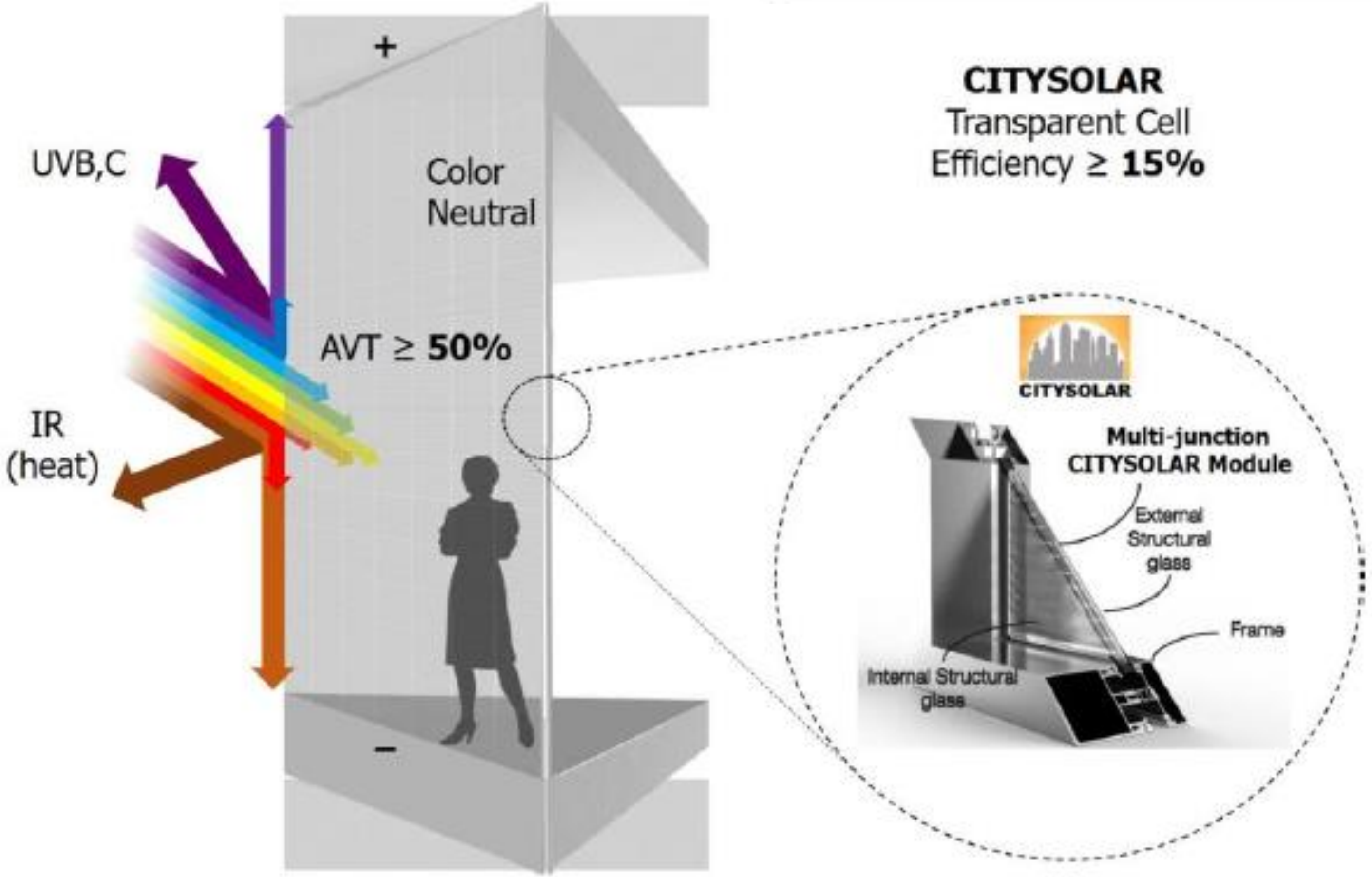
Transparent PV!

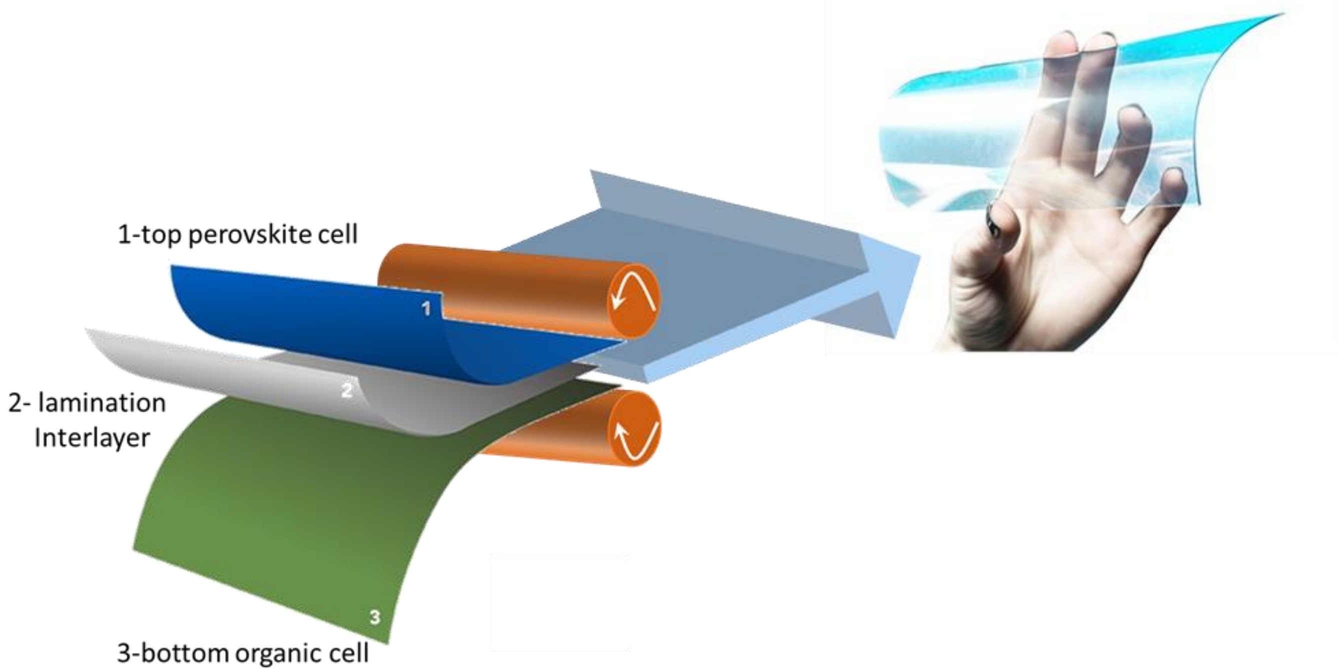
CITYSOLAR

Integration via a lamination process of top NUV Perovskite solar cell and the bottom NIR polymeric solar cell

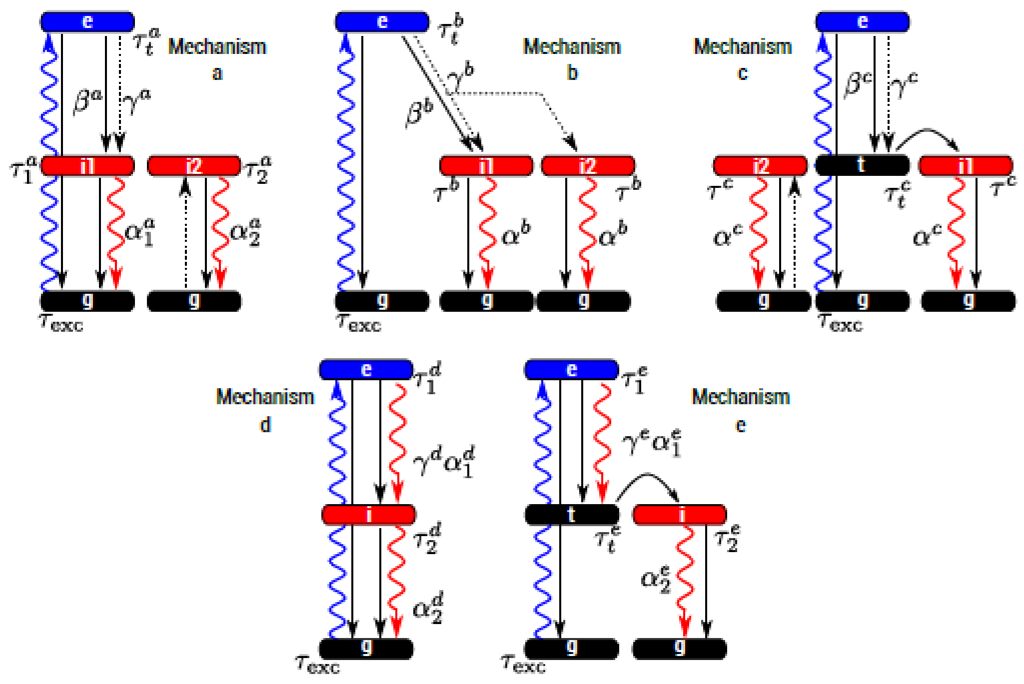








Nouveaux Concepts



1. Conversion de photons (IPVF, Icube)

Nouveaux fluorophores (ICUBE, IPHC, …)

Méthodes de détection, intégration dispositifs (IPVF)

2. Cellules à porteurs chauds (IPVF, C2N, FOTON)

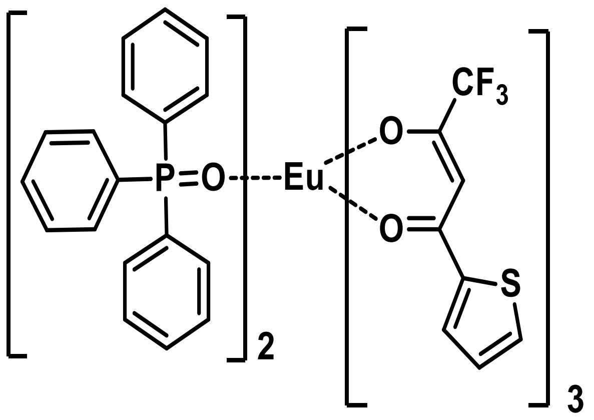
Cellule PV et Thermoélectrique (ANR ICEMAN)

3. Rectenas (IM2NP)

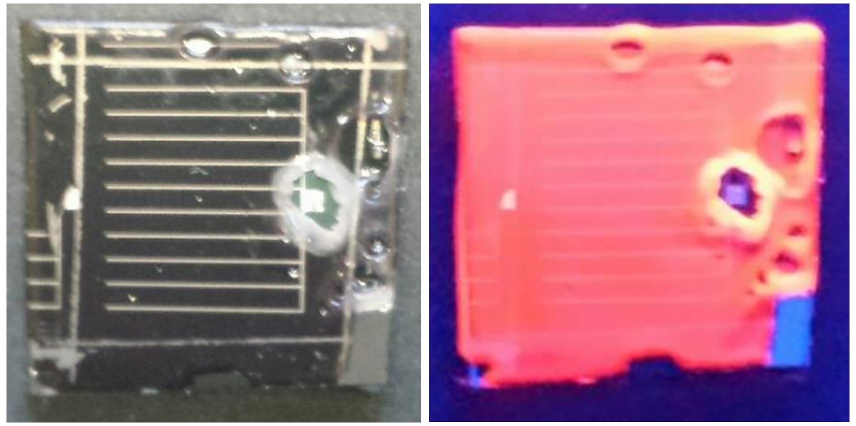
Nanodiodes pour redresser le courant alternatif induit par le rayonnement électromagnétique visible

Functionalised encapsulants

L'encapsulant, utilisé dans des modules : ethylene vinyl acetate (EVA)
Le convertisseur de photons : le complexe de coordination $Eu(tta)_3(tppo)_2$
Les cellules testées : cellules Mo/CIGS/CdS/iZnO/ZnO:Al (IPVF)

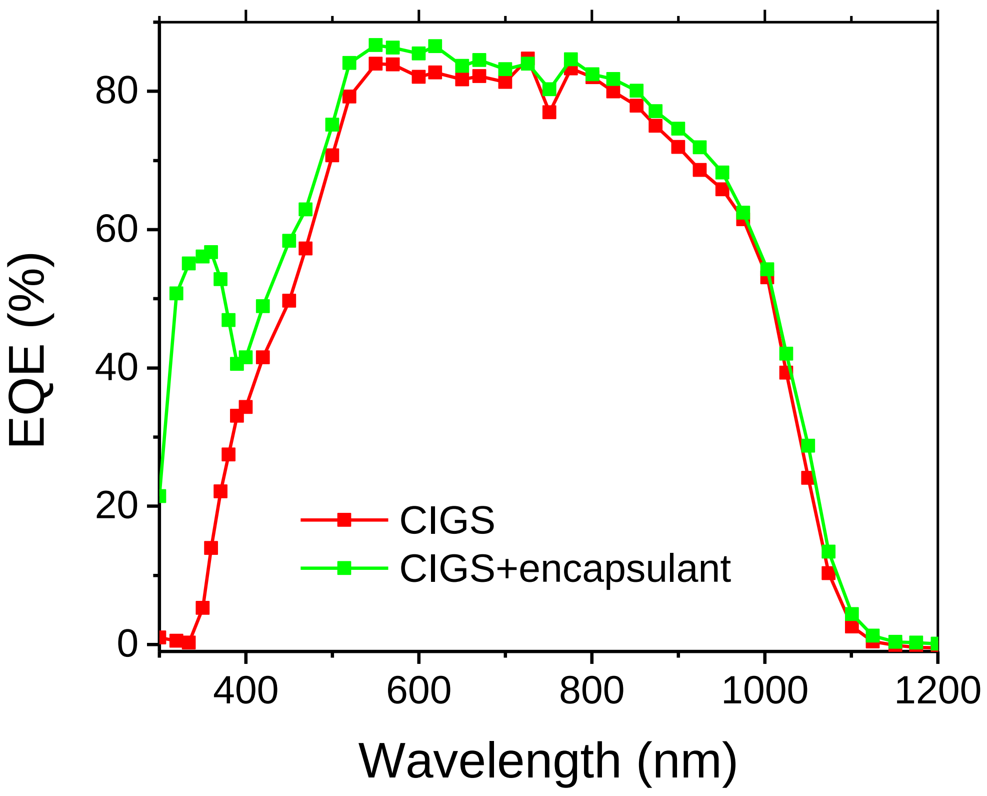


$Eu(tta)_3(tppo)_2$



Lumière visible 350 nm

Cellule CIGS + encapsulant



Gain maximal en J_{SC} : 1.5 mA/cm^2, dont 0.55 mA/cm^2 dus uniquement à la conversion de photons.

Collab.
ICube T. Fix, A. Slaoui
IPHC A. Nonat, L. Charbonnière
IPVF A. Gavriluta, P. Zabierowski, J.F. Guillemoles

L'encapsulant modifié absorbe dans l'UV et émet à 610 nm (Eu). Le rendement quantique de cet encapsulant est évalué à 70%.

A. Gavriluta, T. Fix, Adv. Opt. Mater. ***4****, 1846 (2016)*

Towards downconversion

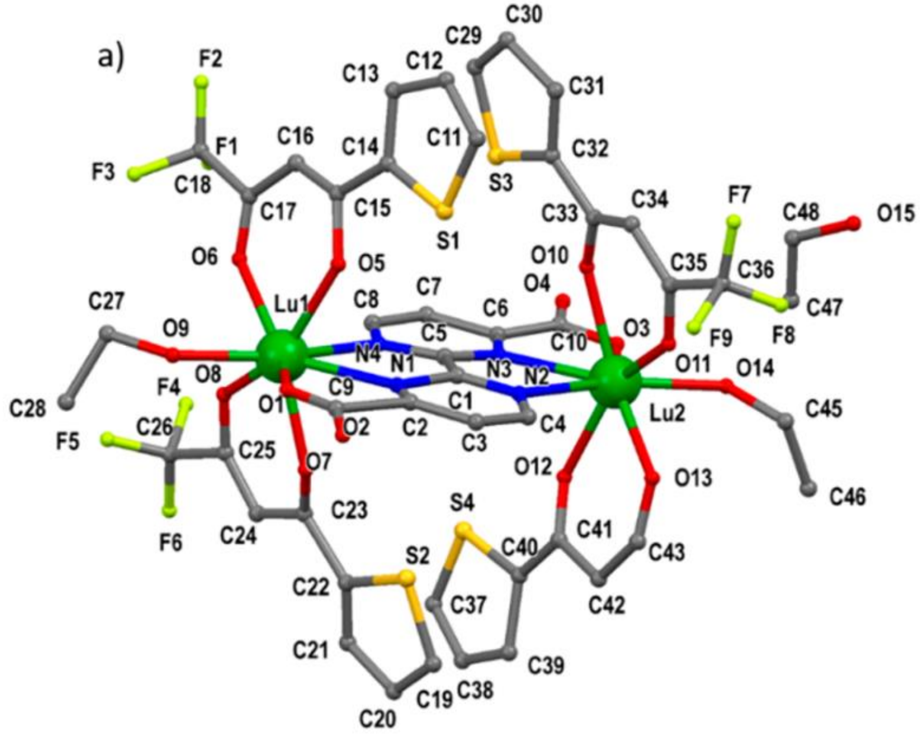
Inorganic Chemistry

pubs.acs.org/IC Article

From Mono- to Polynuclear Coordination Complexes with a 2,2′-Bipyrimidine-4,4′-dicarboxylate Ligand

Piotr W. Zabierowski,* Olivier Jeannin, Thomas Fix, Jean-François Guillemoles, Loïc J. Charbonnière, and Aline M. Nonat*

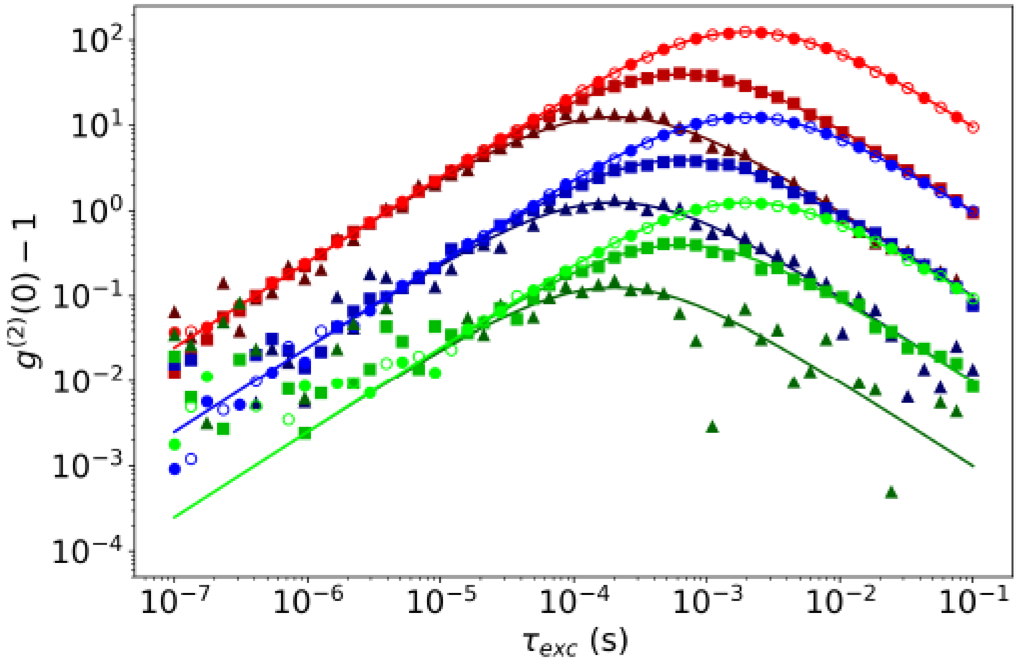
Cite This: *Inorg. Chem.* 2021, 60, 8304–8314 Read Online



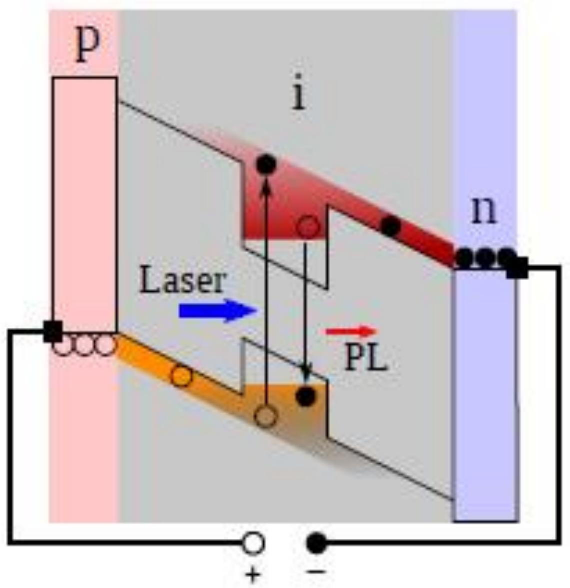
A Bayesian approach to luminescent down-conversion

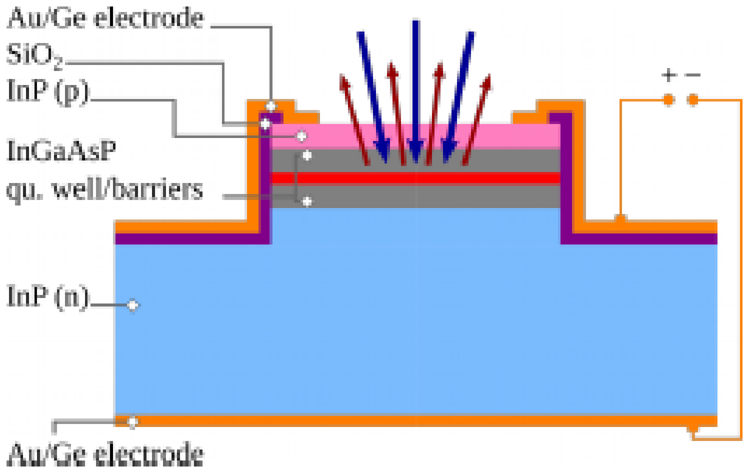
J. Chem. Phys. 154, 014201 (2021); https://doi.org/10.1063/5.0026396

M. Löning[1,a)], L. Lombez[2], J.-F. Guillemoles[1,b)], *and* D. Suchet[1,c)]



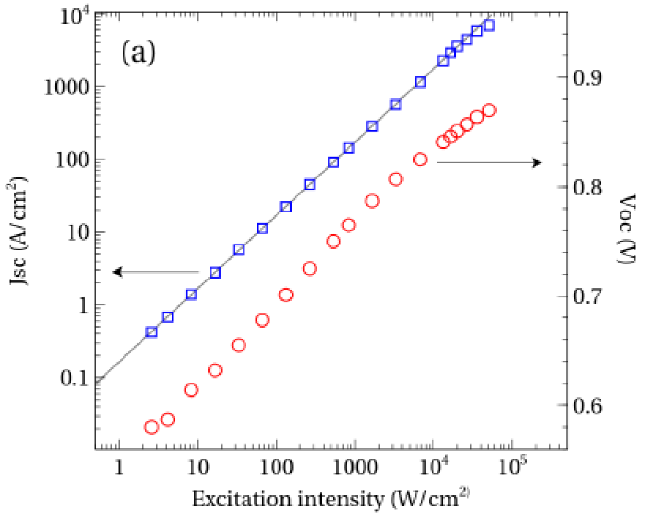
Case Study : Hot Carrier Solar Cells

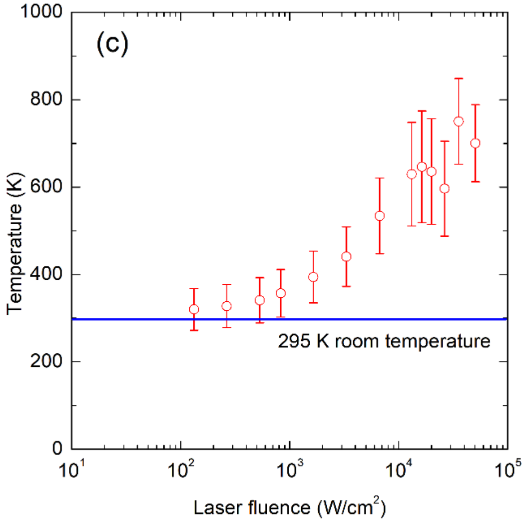




Quantitative experimental assessment of hot carrier-enhanced solar cells at room temperature

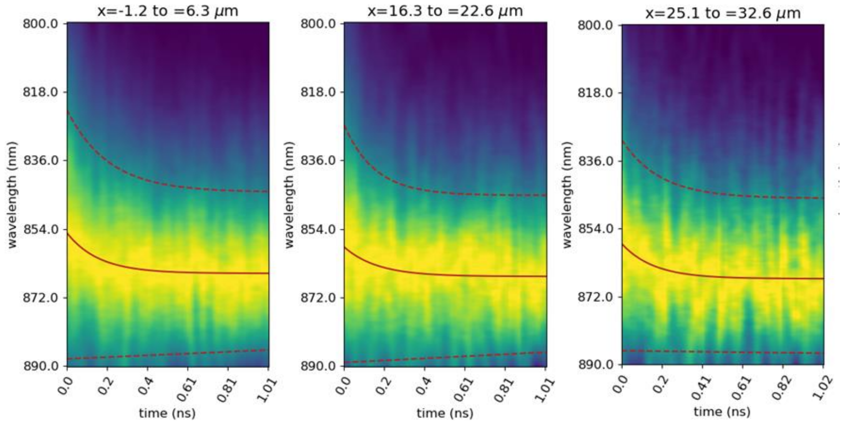
Dac-Trung Nguyen[1], Laurent Lombez[1,2]*, François Gibelli[1,2], Soline Boyer-Richard[3], Alain Le Corre[3], Olivier Durand[3] and Jean-François Guillemoles[1,2]





Trung Nguyen et al. Nature Energy, 2018

- **Small mesa devices (µcells)**
  - ✓ **Low Rs, Heat extraction**
  - ✓ **Linear Jsc up to 10^5 suns**
- **Very thin solar cell (250 nm)**
- **> 600 K electrons @ >15000 suns**



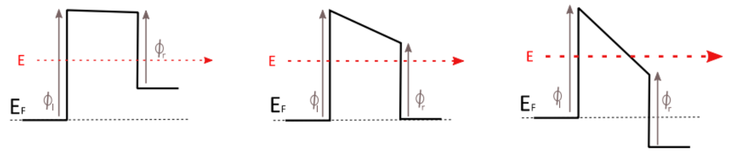
IPVF
UMR 9006
Joint Research Unit

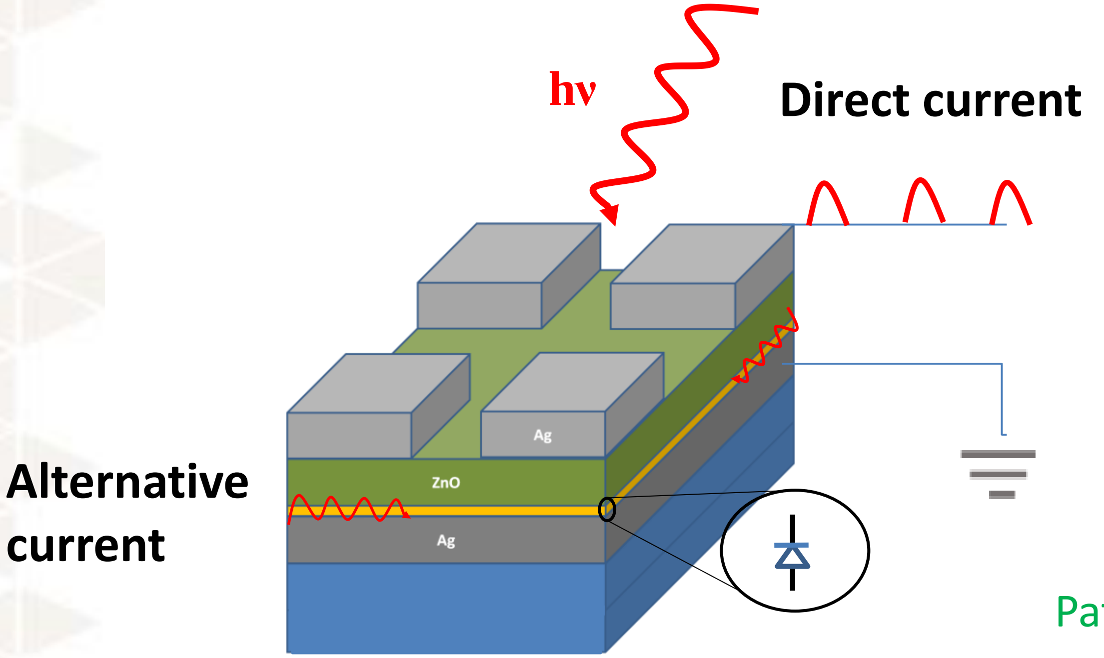
LUMEN-PV team / DETECT department at IM2NP

Institut Matériaux Microélectronique Nanosciences de Provence

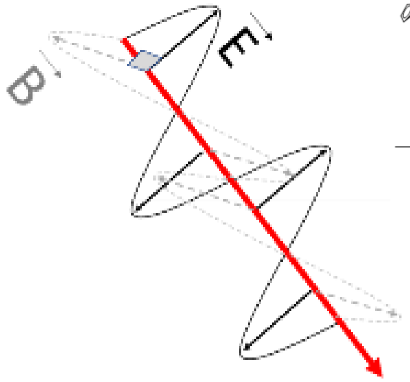
J. Le Rouzo, L. Escoubas, JJ Simon, D. Duché, C. Ruiz-Herrero, M. Pasquinelli

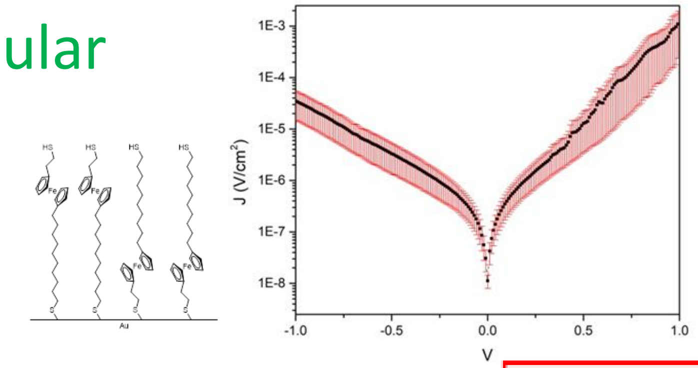
- **Optical rectifying antennas (Rectennas) to generate electricity from light**



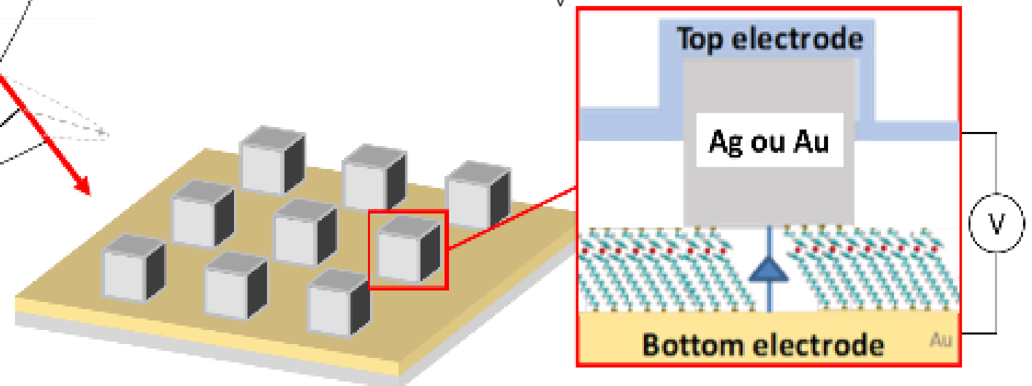


Tunneling molecular and MIM diodes





Patch nano-antennas

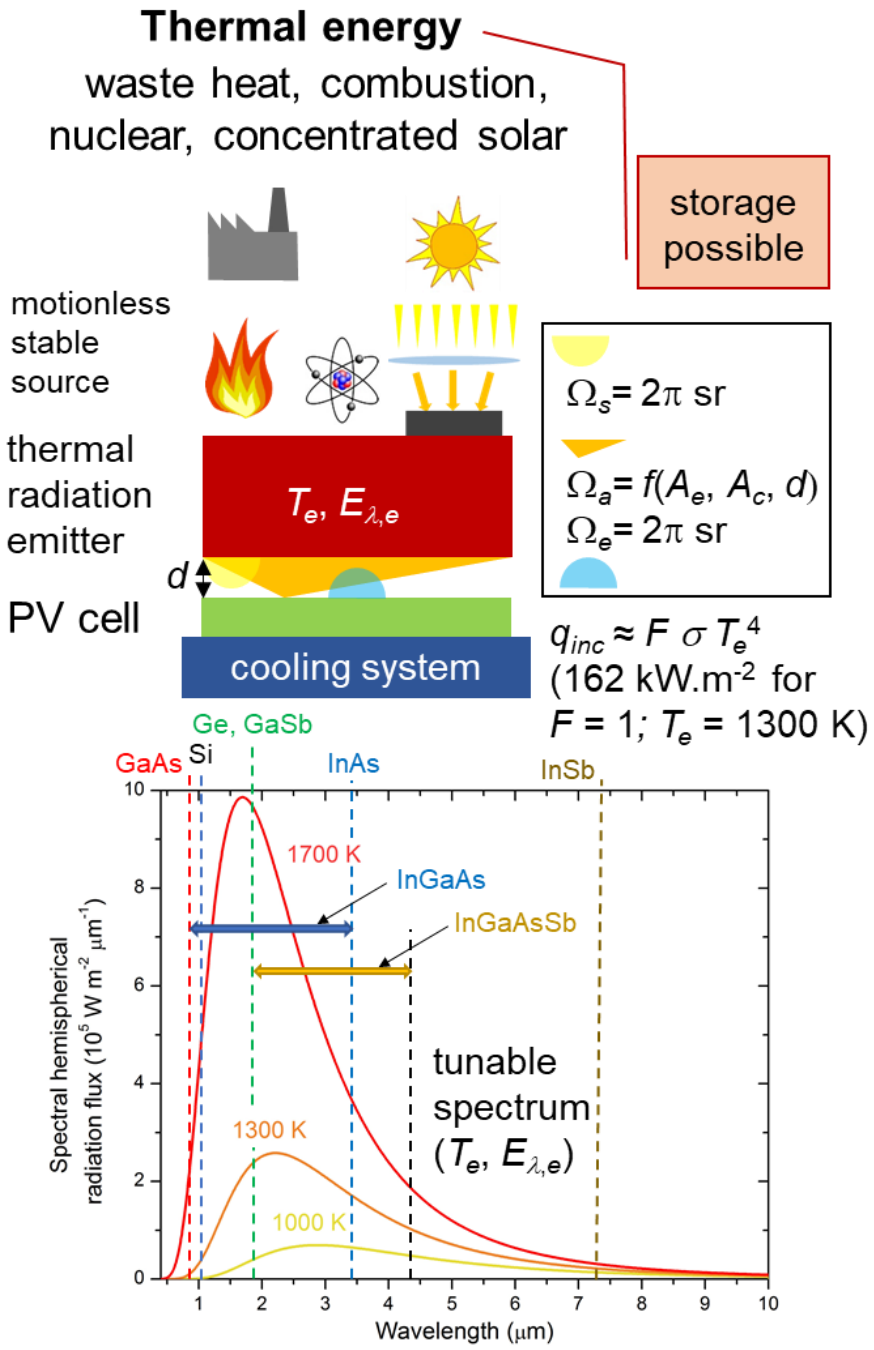


Plasmonic nano-antennas connected with high-frequency molecular diodes

Projects : Rectenna for spatial applications (CNES funding) / CNRS prematuration project Rectolab / ANR 2021 PlasMORE-LIGHT project

- *C. A. Reynaud, D. Duché et al., Advanced Optical Materials 6 (23), 1801177, (2018)*
- *D Duche et al. patent EP 3 493 283 A1 (2017) / US Patent App. 16/762,126 (2020)*
- *L. Escoubas et al. Prog. Quantum Electron. 2019, 63, 1*
- *Vikas Jangid, et al., MRS Advances 5 (61), 3185-3194 (2020)*

Nouvelles applications



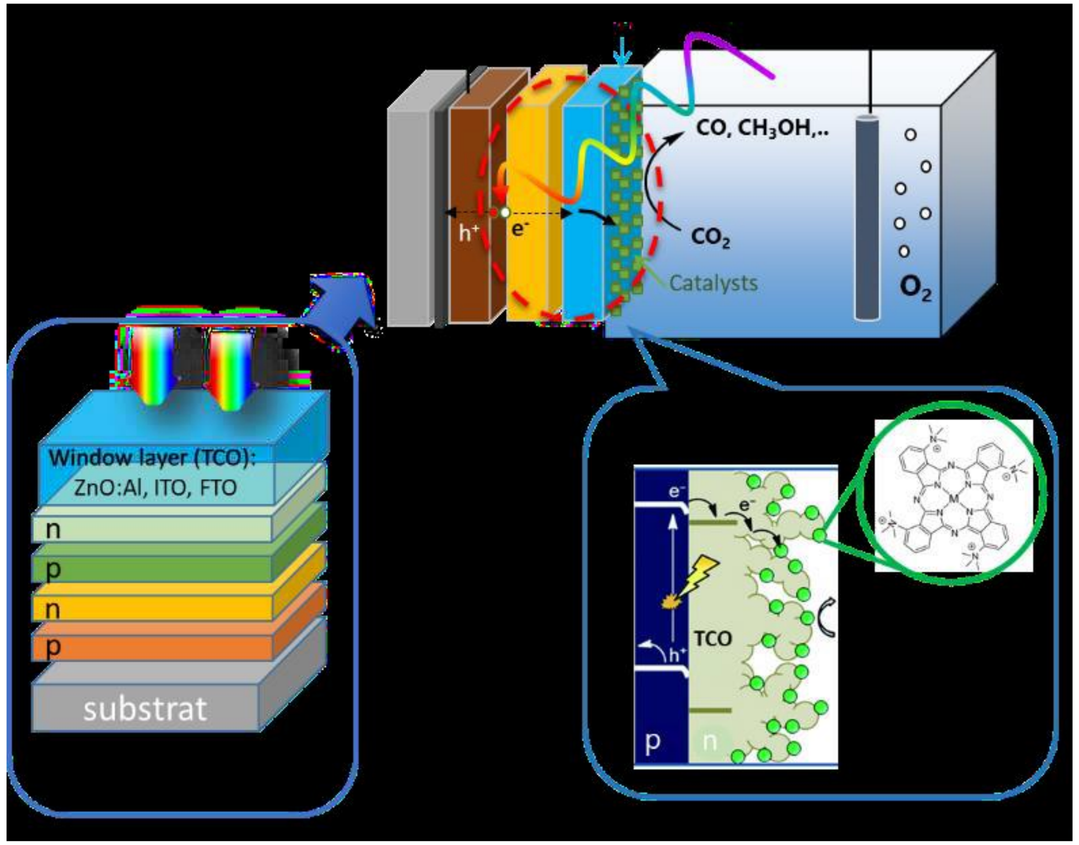
(Datas & Vaillon, chapitre de livre, Elsevier, 2020)

1. Récupération de chaleur Haute température (IES, CETHIL, ESYCOM, Institut P', L2C)

Thermophotovoltaique : émetteur selectif et PV opérant dans IR

2. Solar fuels (IPVF, LPICM, ILV,…)

Photoréduction du CO2 (Collab. LEM)

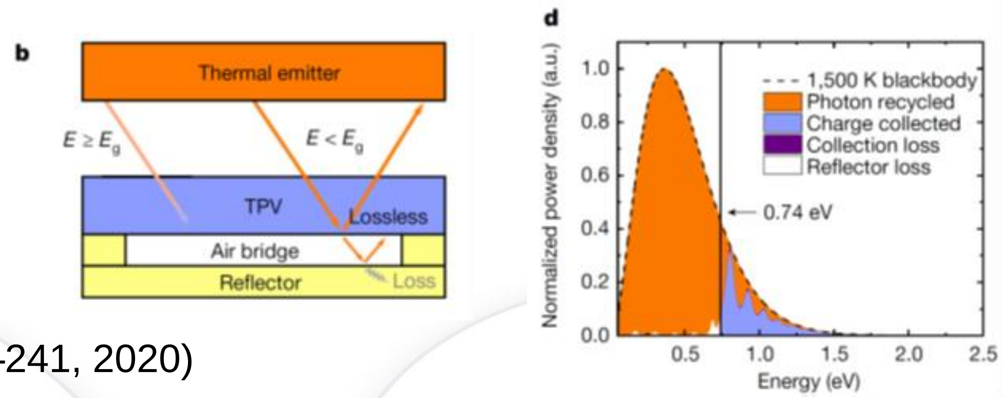


Etat de l'art

Rendements records

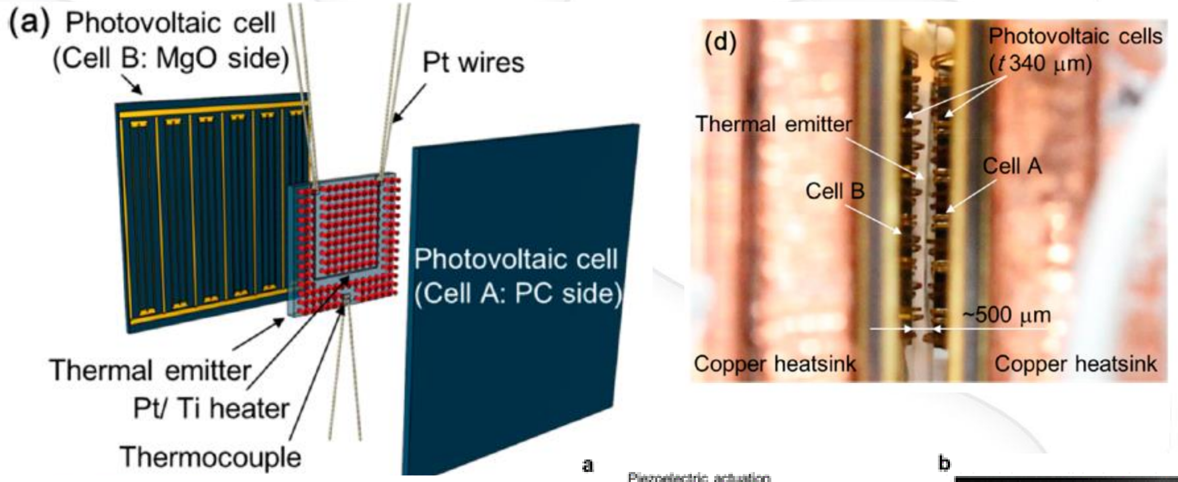
Cellules TPV mono-junction (InGaAs) : 29 – 32% en améliorant le recyclage des photons vers l'émetteur thermique (T ~ 1200 ºC)

(Omair et al., PNAS 116, 15356-15361, 2019; Fan et al., Nature 586, 237–241, 2020)



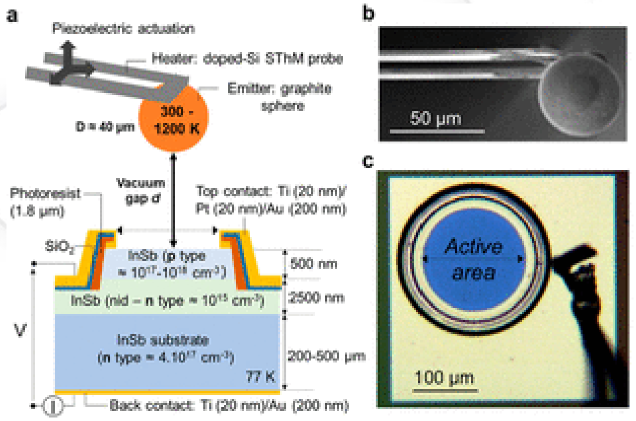
Système TPV (cellule InGaAs) : 11,2%
p_{max} = 0,368 W / cm^2 (T ~ 1065 ºC)

(Sakakibara et al., ACS Photonics 7, 80-87, 2020)



Cellule TPV en champ proche (cellule InSb @ 80 K) : 14%
p_{max} = 0,75 W / cm^2 (T ~ 460 ºC)

(Lucchesi et al., Nano Letters 21, 4524-4529, 2021)



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Les programmes

Projets ANR

Projets Europe

Projets IPVF

IPVF Background and Key Figures

Program I
Economy & Market assessment

Program II
Perovskite on Silicon tandem modules for industrialization

Program III
Low-cost III/V on Silicon tandem cells

Program IV
Advanced Characterization
Theory & Modelling

Program V
Solar-to-Fuel

Program VI
Proof of concept breakthroughs

The Institut Photovoltaïque d'Ile-de-France (IPVF),

Initiative launched by the French Government in 2013

Located on the Paris Saclay Research Campus since 2018

Collaborative solar cell research platform,

3500 m² of lab space, 150 researchers, 25 nationalities

Public-Private Partnership,

From fundamental science to application

Enabling center for research and industrialization