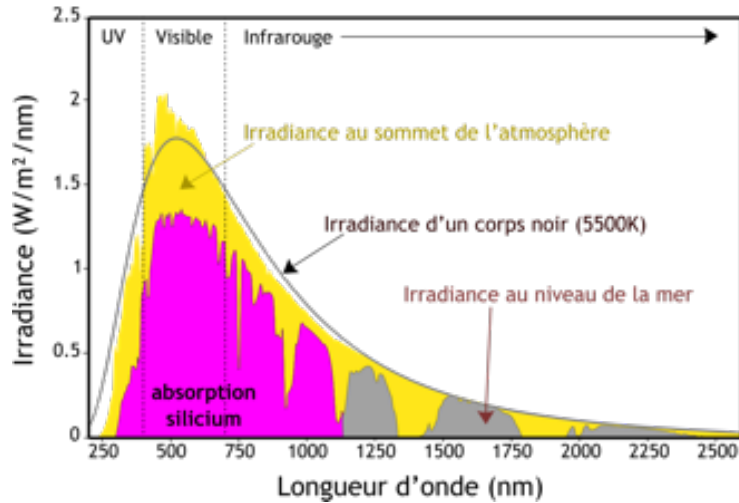


Apport des nanos au photovoltaïque

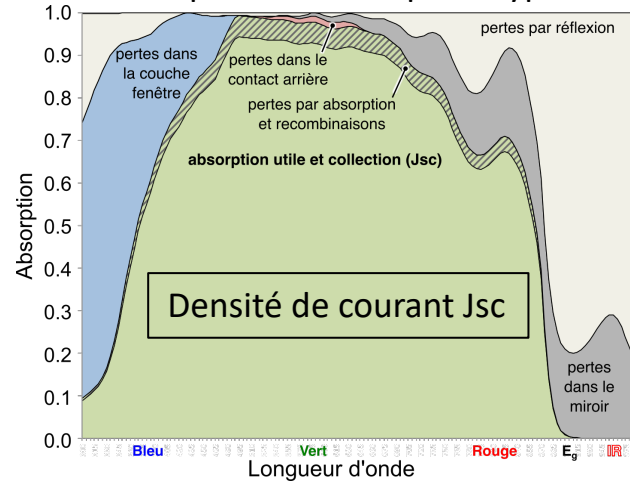
1. Nanostructuration pour le piégeage optique,
la gestion de la couleur et le refroidissement thermique
[surface]
2. Nanomatériaux
[volume]
3. Caractérisation à l'échelle nanométrique
[surface et volume]

La lumière du soleil : absorption et pertes optiques dans une cellule solaire

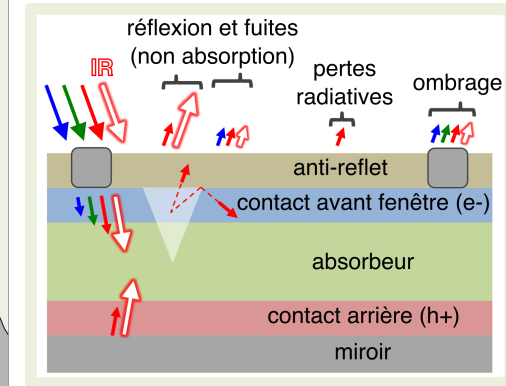
Spectre d'irradiance solaire



Spectre d'absorption type



Pertes optiques



Matériaux :

- ~160 μm de **silicium** (bande interdite indirecte)
- ~2-4 μm de **GaAs** (spatial), CdTe, Cu(In,Ga)Se₂,...

Enjeux :

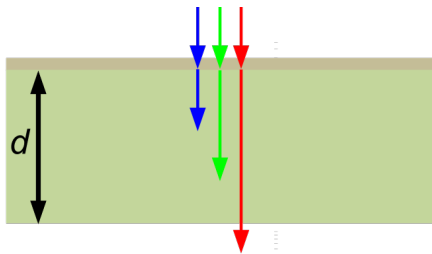
- Réduire les pertes optiques
- Diminuer l'épaisseur

Comment absorber + avec – de matière ?

Le chemin optique peut être *augmenté d'un facteur F* par piégeage optique pour compenser la faible absorption de couches ultrafines.

$$A = 1 - e^{-Fad}$$

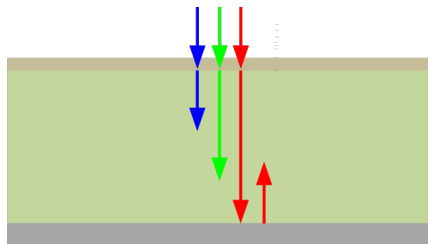
couche anti-reflet
(double)



(a) absorption simple passage

$$F = 1$$

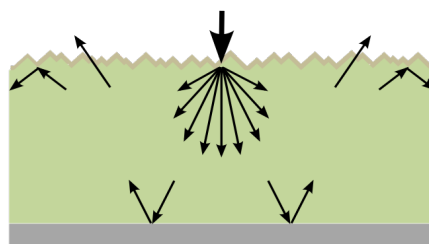
+ un miroir arrière



(b) double passage

$$F = 2$$

structuration aléatoire
micronique

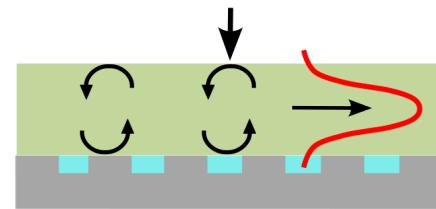


(c) diffusion lambertienne

$$F = 4 n^2 \approx 50$$

Aller-retour oblique $\rightarrow \times 4$
Réflexion interne $\rightarrow \times n^2$

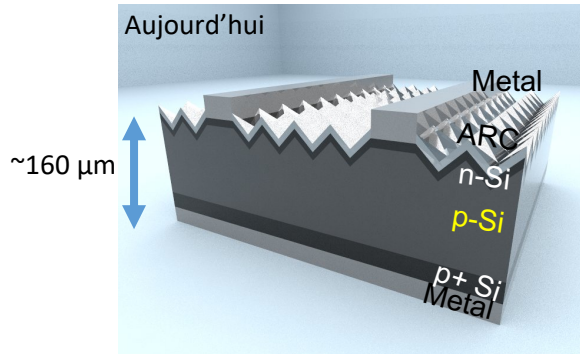
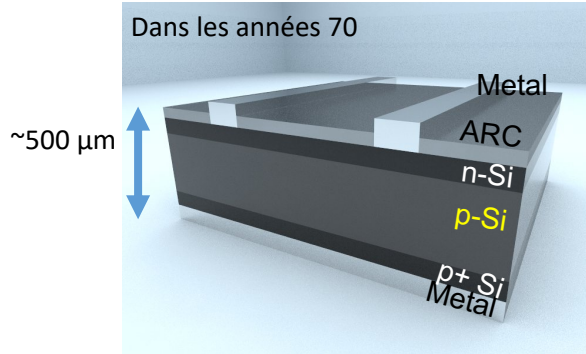
structuration périodique
nanométrique



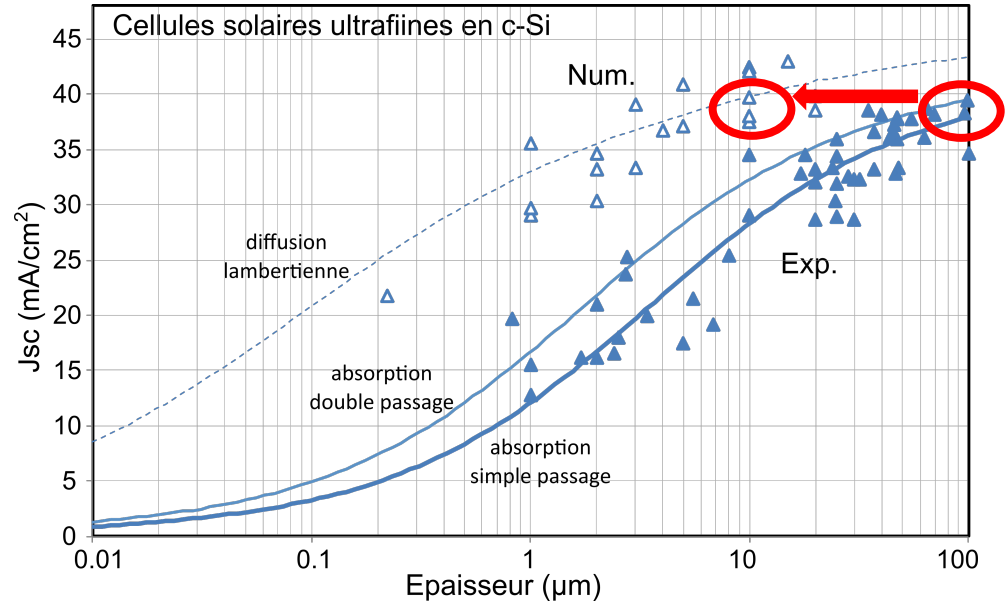
(d) absorption multi-résonante

$$F > 50$$

Des cellules solaires en silicium de plus en plus fines



De nombreux efforts pour diminuer l'épaisseur d'un facteur 10.

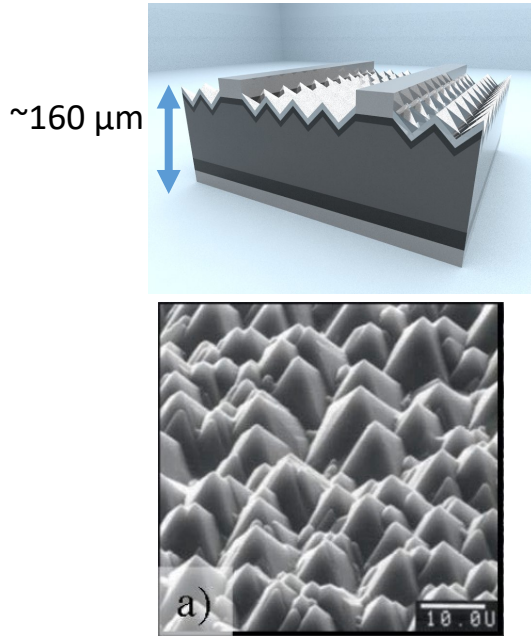


I. Massiot, A. Cattoni, S. Collin, **Nature Energy** 5, 957-972 (2020)

Des cellules solaires de plus en plus fines

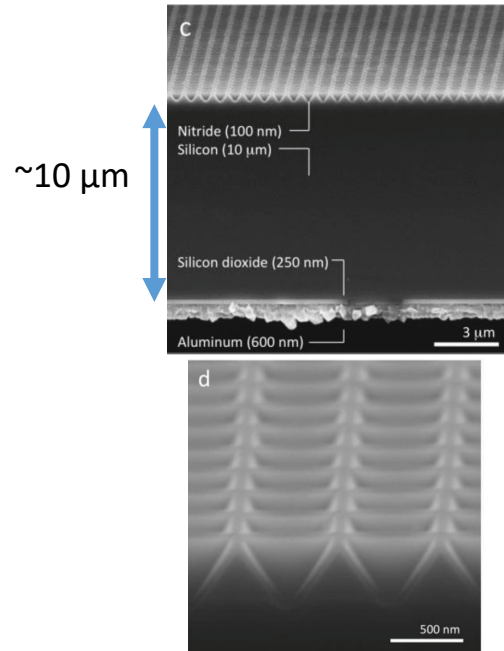
Aujourd'hui sur les toits :

20 % d'efficacité avec 160 μm

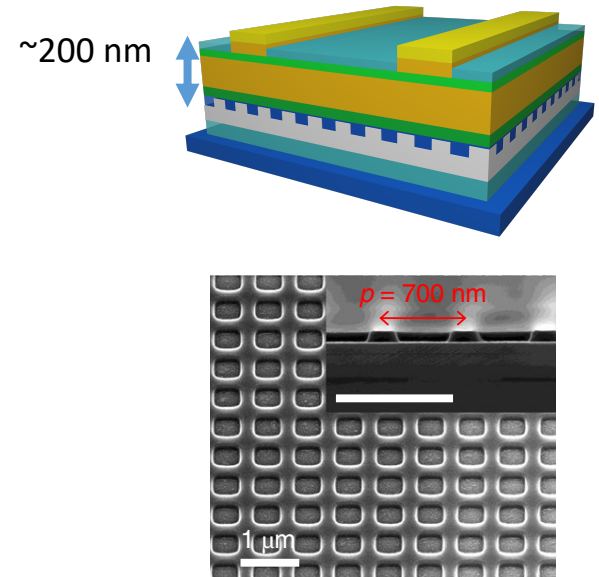


Aujourd'hui dans les laboratoires :

15,7 % d'efficacité avec 10 μm de silicium



20 % d'efficacité avec 0.2 μm de GaAs



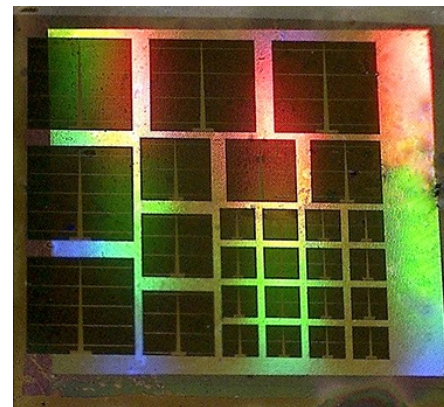
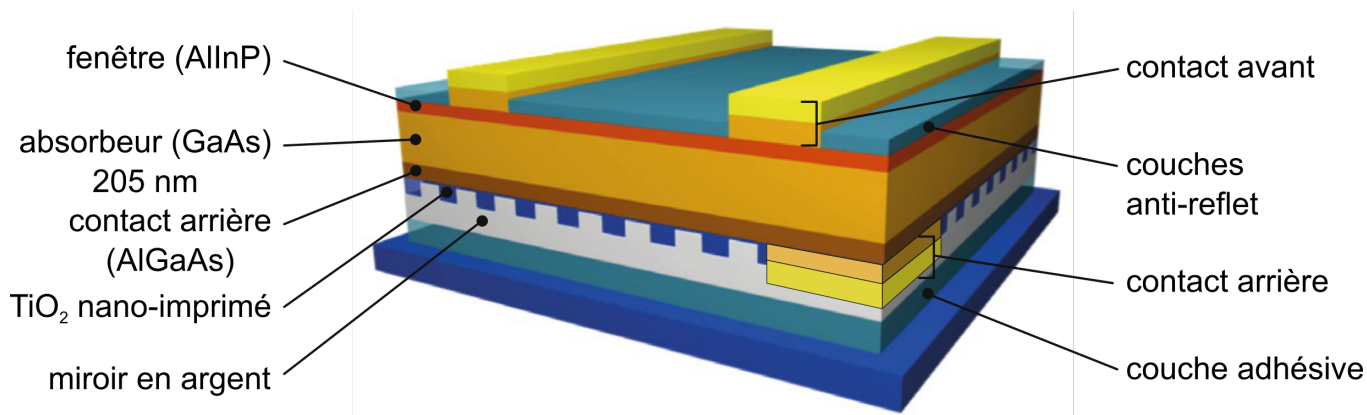
Des cellules solaires ultrafines en GaAs : 20% avec seulement 200 nm

*L'apport de la nanophotonique :
preuve de concept d'une absorption multi-résonante
dans une cellule 10 fois plus fine que les cellules en GaAs conventionnelles de $2\text{ }\mu\text{m}$.*

nature
energy

Nature Energy 4, 761-767, 2019

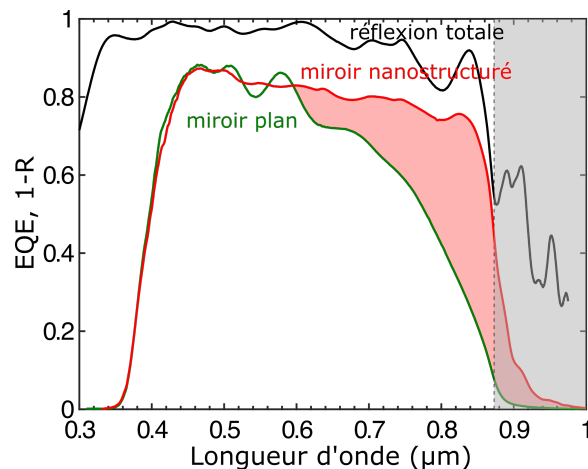
H.-L. Chen et al.
C2N, collab. Fraunhofer ISE



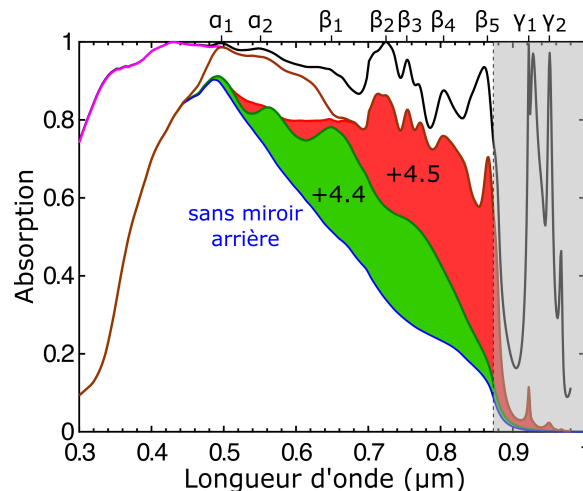
Une fabrication par nanoimpression et transfert de couches.

Des cellules solaires ultrafines en GaAs : 20% avec seulement 200 nm

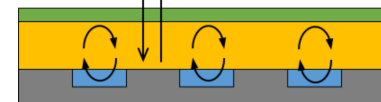
Mesures



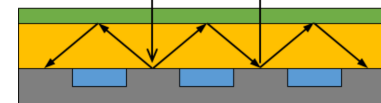
Simulations



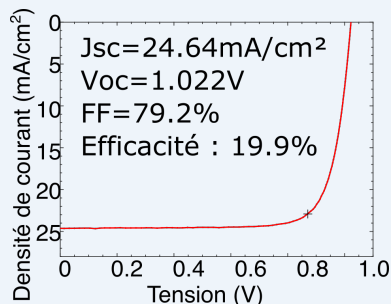
Résonances de Fabry-Pérot



Résonances de modes guidés



Mesure sous
simulateur
solaire



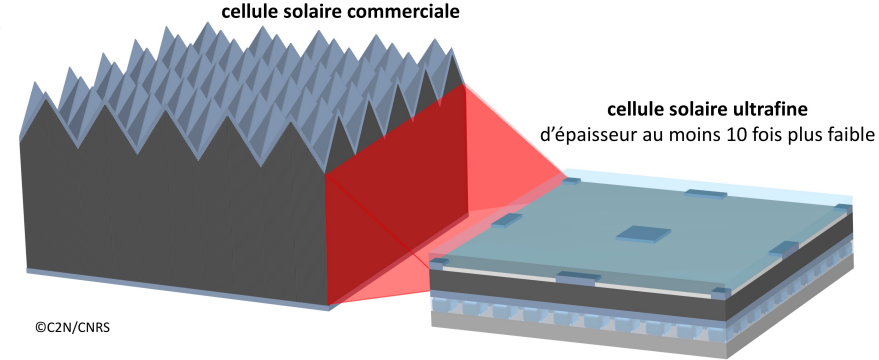
- Des performances optiques très proches des simulations
- Une efficacité record de 19.9% (certifiée)
- Une analyse des pertes qui montre le chemin pour atteindre 25% à brève échéance

Nature Energy 4, 761 (2019)

Cellules solaires ultrafines : conclusion

La nanophotonique permet de piéger la lumière et de diminuer l'épaisseur des cellules solaires sans perte d'absorption.

- moins de matériaux, des procédés plus rapides,
pour des cellules moins chères
- des cellules flexibles et légères
pour de nouvelles applications
- des cellules plus résistantes aux radiations,
pour le spatial



Pour en savoir plus : <https://sunlit-team.eu>

Nanophotonique pour le PV : un large panorama sur les cellules solaires ultrafines

I. Massiot, A. Cattoni, S. Collin, Nature Energy 5, 957-972 (2020)

Un panorama plus court et en français

A. Cattoni, S. Collin, **Photoniques 102**, 44-48, Mai-Juin 2020

20% d'efficacité avec 200 nm de GaAs, le record !

H.-L. Chen, A. Cattoni, (...) S. Collin, **Nature Energy 4**, 761 (2019)

Photonic and thermal properties of butterfly *Asterope Leprieuri* to improve solar cells

*Anne-Laure Joudrier^{*1}, Amélie Chervet², Sophie Cassaignon³, Serge Berthier⁴, Jean-François Guillemoles²*

¹IPVF - ENSCP Chimie Paristech PSL, Palaiseau, France

²IPVF - CNRS, Palaiseau, France

³LCMCP, Sorbonne Université, Paris, France

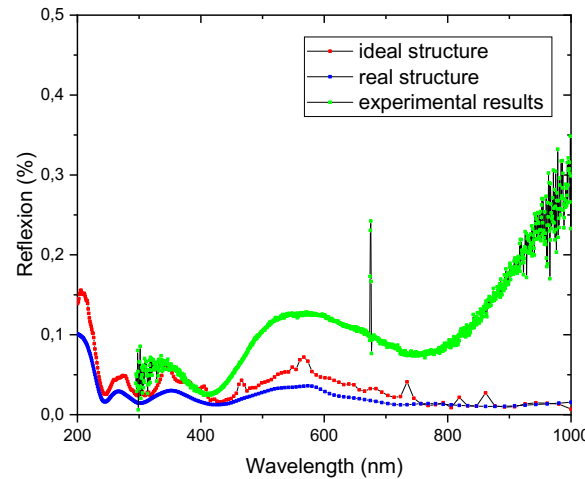
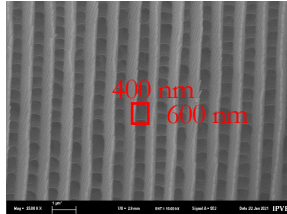
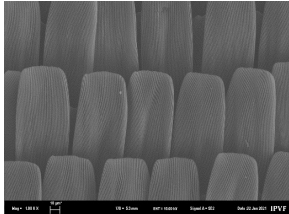
⁴INSP, Université de Paris, Paris, France

[*anne-laure.joudrier@chimieparistech.psl.eu](mailto:anne-laure.joudrier@chimieparistech.psl.eu)

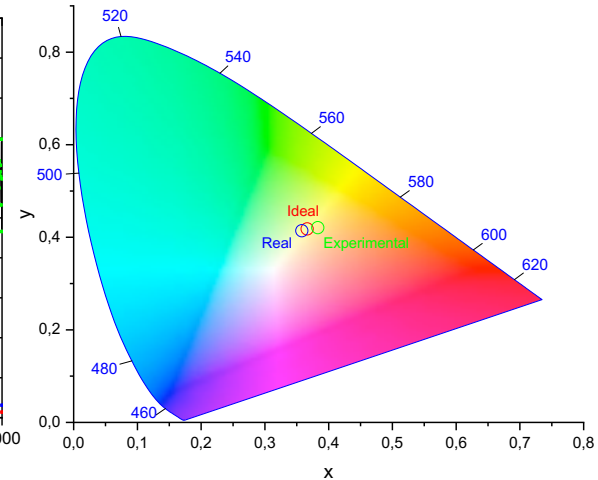
- The aim of the project is to adapt properties of biological material (for example, butterfly wings...) to solar cells, both in terms of photonics (visual aspect, colours), and in terms of absorption and thermal regulation.
- It will allow a better integration of photovoltaic devices to the environment and the buildings.



Blue part of the wing



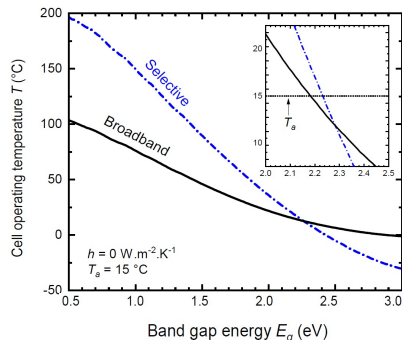
Chromaticity diagram CIE 1931



- **RADIATIVE SKY COOLING (RSC) OF SILICON SOLAR CELLS AND MODULES**
- Improving efficiency and long-term reliability by passively lowering the operating temperature
Jérémy Dumoulin, Emmanuel Drouard, Mohamed Amara

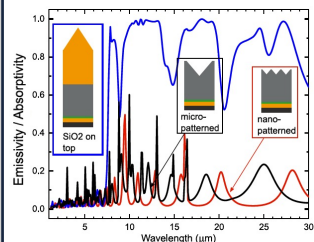
Fundamental thermoelectric modelling

- ✓ Theoretical basics for RSC of photovoltaic (PV) devices
- ✓ Determining the ideal thermal emissivity profile for single-junction cells
- ✓ Quantifying the potential benefit of enhanced RSC



Dumoulin et al. *Sustain. Energy Fuels*. 2021

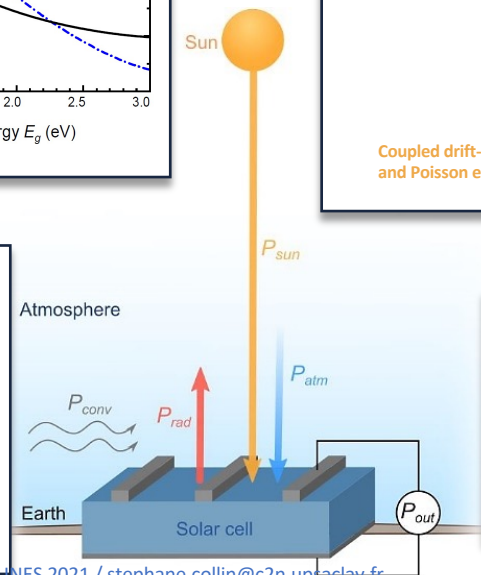
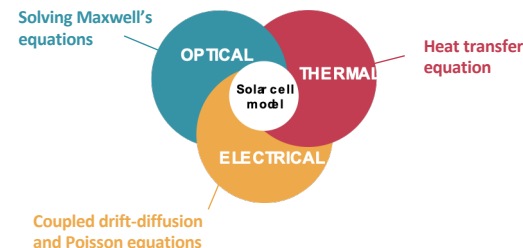
Investigation of photonic pathways for enhanced RSC



- ✓ Broadband optical simulation of an entire PV module
- ✓ Micro and nano patterning (device fabrication)

Detailed opto-electro-thermal simulation using COMSOL Multiphysics

- ✓ Detailed modelling of silicon devices in order to accurately predict the opto-electro-thermal behavior from the bottom-up
- ✓ Full multiphysics coupling



Material and device characterization

- ✓ Measuring the complex refractive index of PV module materials in the near and middle infrared
- ✓ Measuring the thermal emissivity profile of solar cells and modules

- Relate the appearance of the resonances (width, position) of the CPs to the colors (chromaticity & brightness)
- In the longer term: at a given color (mixture of lines), how to choose the CP that penalizes a cell the least?

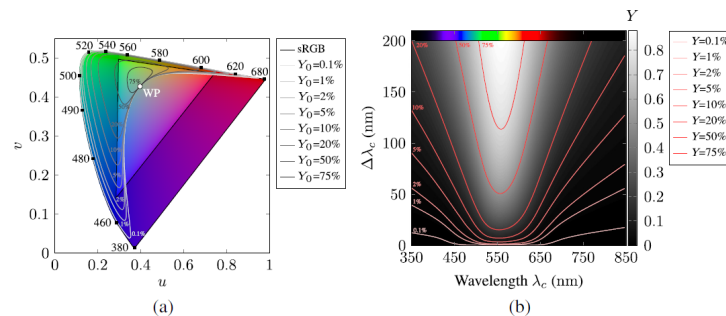
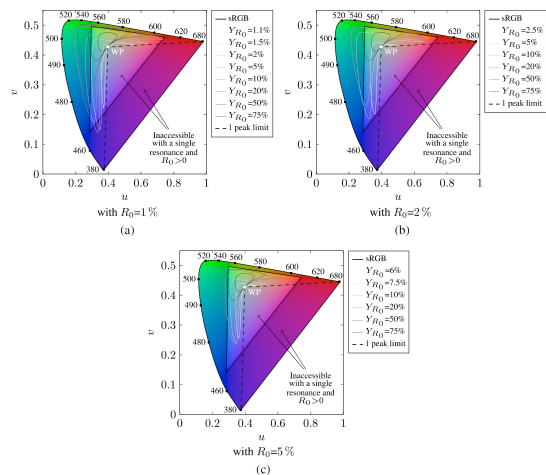
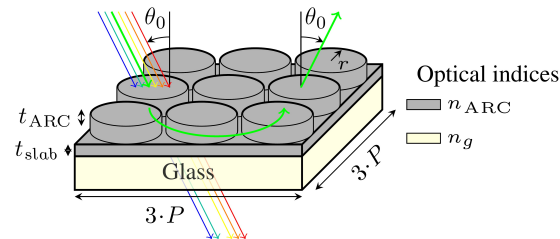


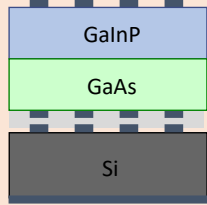
Fig. 3 Iso luminance curves for an ideal case with no constant reflection in the visible range ($R_0 = 0$). (a) Chromaticity diagram of with few iso luminance curves and (b) relation between the wanted color (λ_c) and the width of the reflected signal ($\Delta\lambda_c$). On top of the figure, hue is given for illustration purpose.

Apport des nanos au photovoltaïque

1. Nanostructuration pour le piégeage optique,
la gestion de la couleur et le refroidissement thermique
[surface]
2. Nanomatériaux
[volume]
3. Caractérisation à l'échelle nanométrique
[surface et volume]

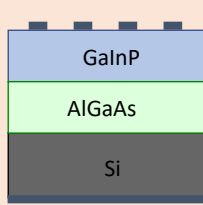
III-V/Si tandem solar cells

Mechanical stacking :



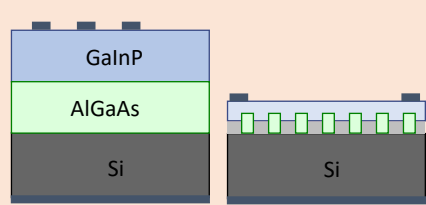
$\eta = 35.9\%$
S. Essig et al.
Nat. Energy
2017

Direct wafer bonding :



$\eta = 35.9\%$
Fraunhofer ISE
2021

Monolithic epitaxial growth:



$\eta = 25.9\%$
M. Feifel et al.
Solar RRL
2020

*localized growth
(under devpt at IPVF)*



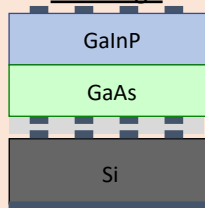
Croissance directe sur silicium

Cellules solaires à nanofils III-V sur Si
Micro-cristaux III-V sur Si

Cellules solaires à nanofils III-V sur Si

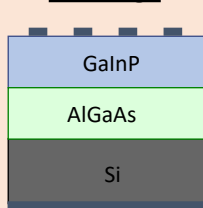
Andrea Cattoni, Capucine Tong, A. Delamarre, S. Collin et al. (C2N, IPVF)

Mechanical stacking :



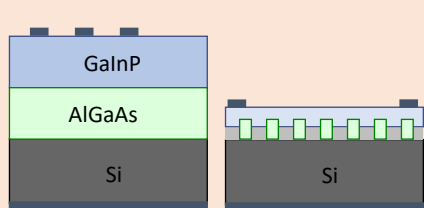
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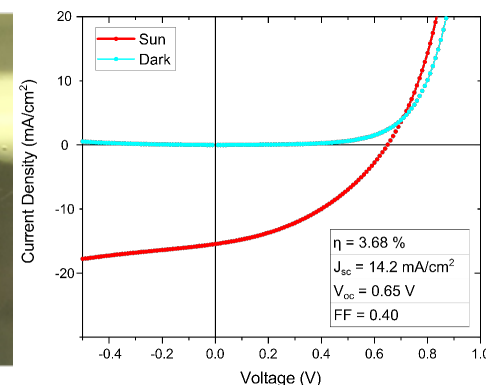
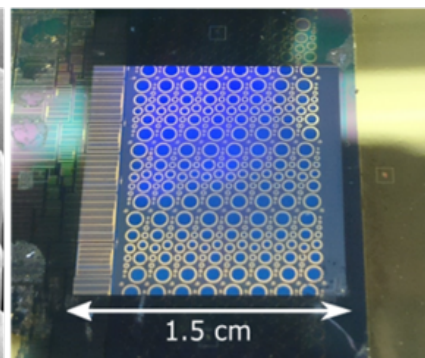
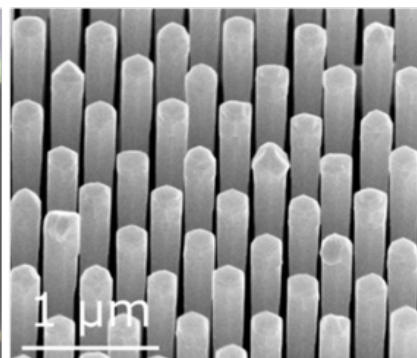
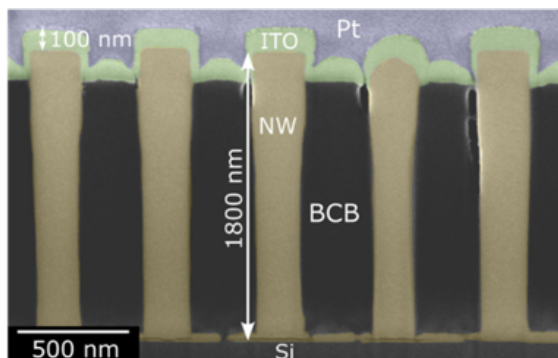
$\eta = 25.9\%$
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Solar RRL
2020

localized growth
(under devpt at IPVF)

Croissance directe sur silicium

Cellules solaires à nanofils III-V sur Si

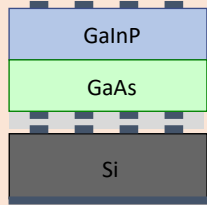
- Croissance directe sur Si
- Un matériau III-V à l'état de l'art
- Un défi technologique pour maîtriser les contacts et proposer des procédés compatibles avec l'industrie



$V_{oc} = 0.65 \text{ V}$ and $\Delta\mu = 0.88 \text{ eV}$ at 1 sun ($\Delta\mu = 1.0 \text{ eV}$ at 187 suns)

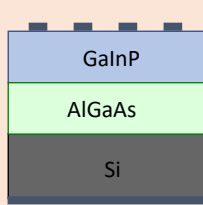
Micro-cristaux III-V sur Si

Mechanical stacking :



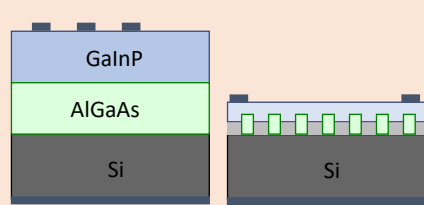
$\eta = 35.9\%$
S. Essig et al.
Nat. Energy
2017

Direct wafer bonding :



$\eta = 35.9\%$
Fraunhofer ISE
2021

Monolithic epitaxial growth:



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M. Feifel et al.
Solar RRL
2020



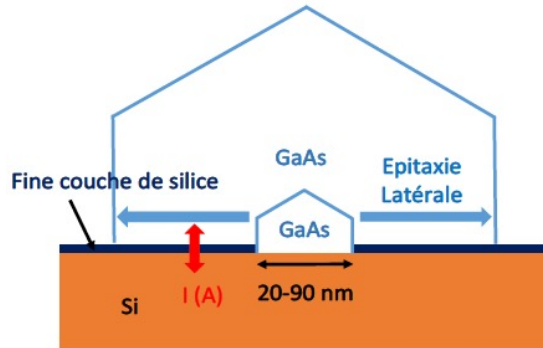
localized growth
(under devpt at IPVF)

Croissance directe sur silicium

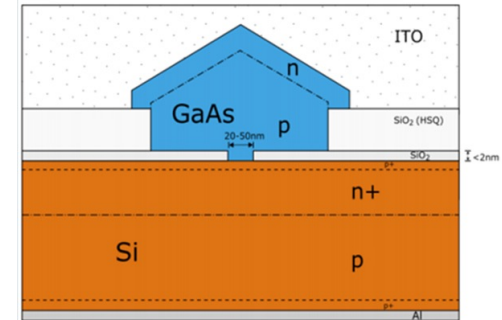
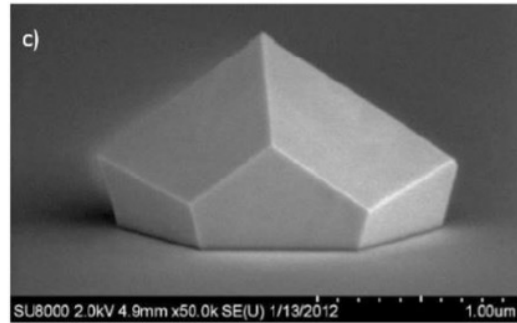
Micro-cristaux III-V sur Si

Participants :

- GeePs (caractérisations): Guillaume Chau (PhD), Alexandre Jaffré, Jose Alvarez, Alexandre Jaffré, Denis Mencaraglia
- C2N (croissance et techno) : Guillaume Chau, Géraldine Hallais, Charles Renard



Epitaxial Lateral overgrowth on Tunnel Oxide from nano-seed (ELTON)



C. Renard et al, Sci. Rep. 6, 25328 (2016)

ANR Project between LIMMS and IMS through the IRP “NextPV”

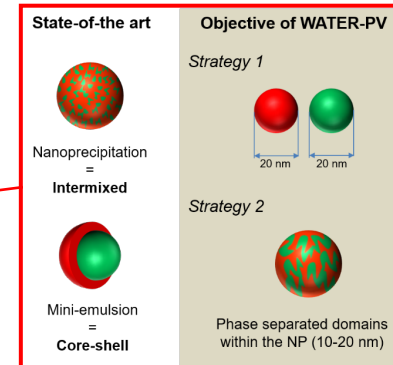
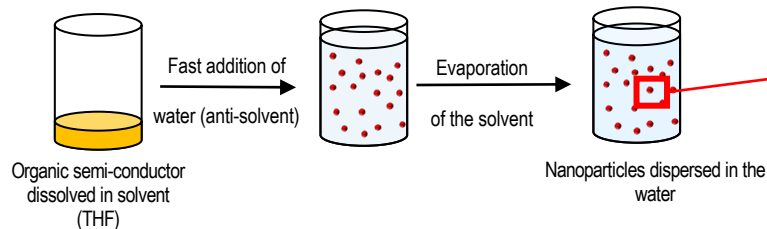
- Coordinator: Sylvain Chambon (LIMMS)
- Three partners:
 - In Japan:
 - LIMMS (IIS, Hirakawa Lab, Fujii Lab)
 - NextPV (RCAST, Segawa Lab)
 - In France:
 - IMS (NextPV, ELORGA)
- External collaborator: University of Sydney



Objective: reduce the environmental footprint of organic photovoltaic technology

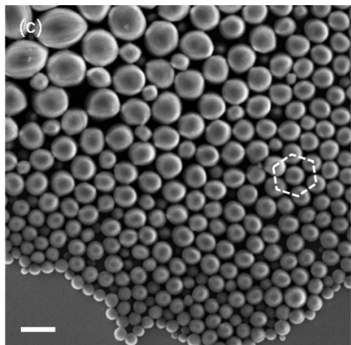
→ Development of water-based organic semiconductor NP in water with well defined morphology for highly efficient OPV devices

Nanoprecipitation: a surfactant-free technique to synthesise organic semiconductor NP

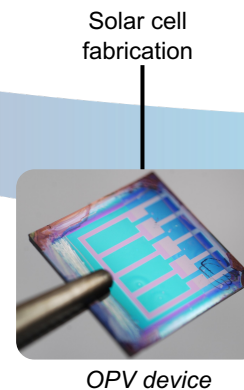
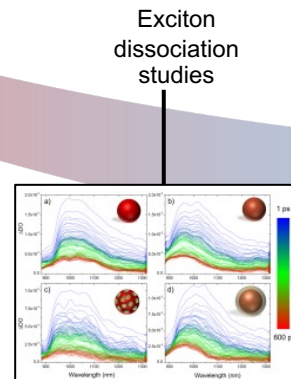
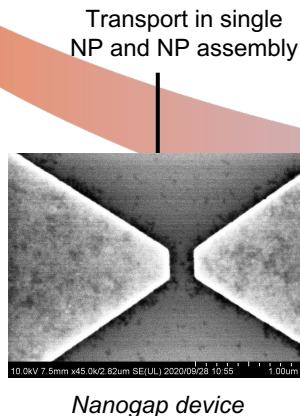
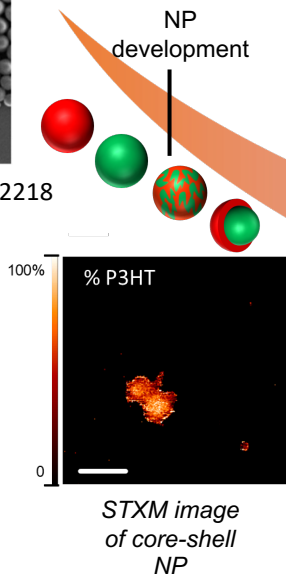


WATER-PV aims at developing environmentally friendly process for the fabrication of highly efficient OPV devices through water-based colloidal inks.

- WP1: Development of well-defined NP using microfluidic systems
- WP2: Identification of the optimum NP design for efficient charge transport and exciton dissociation in NP and thin films
- WP3: OPV device fabrication with optimum performances

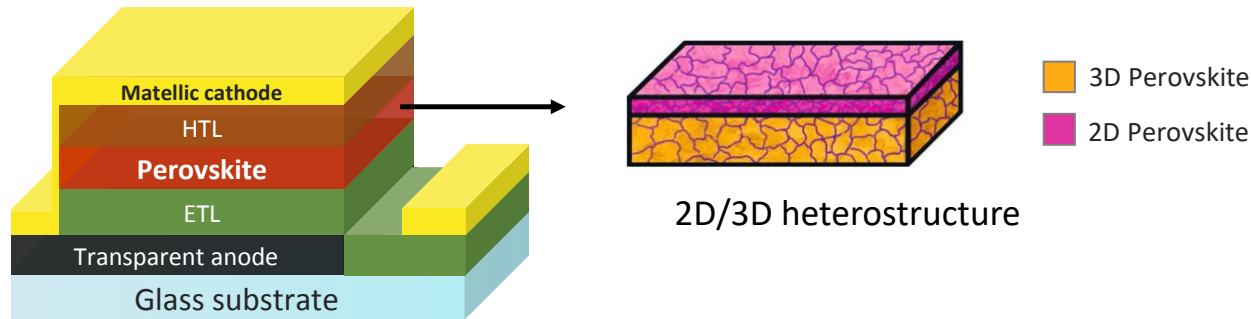


Mater. Chem. Front., 2021, 5, 2218



2D/3D halide perovskite heterostructures for photovoltaïcs

T. Campos PhD, E. Deleporte (LuMIn), A. Duchatelet (IPVF), J. Rousset (IPVF), D. Garrot (GEMaC)



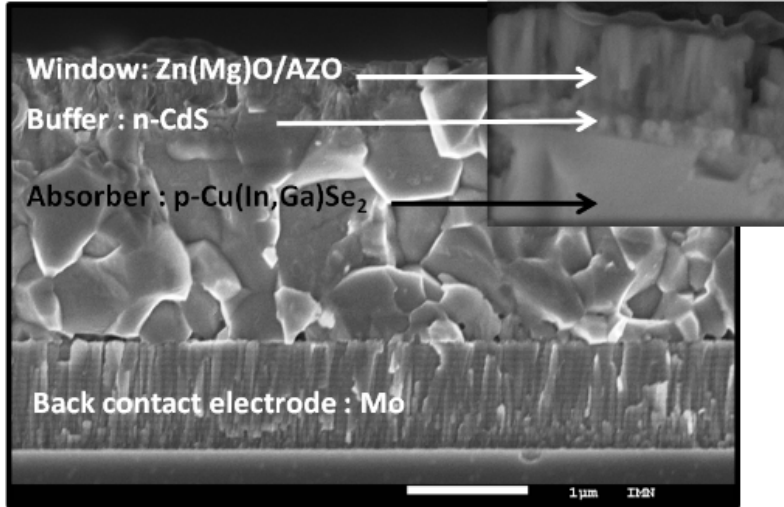
Interface engineering



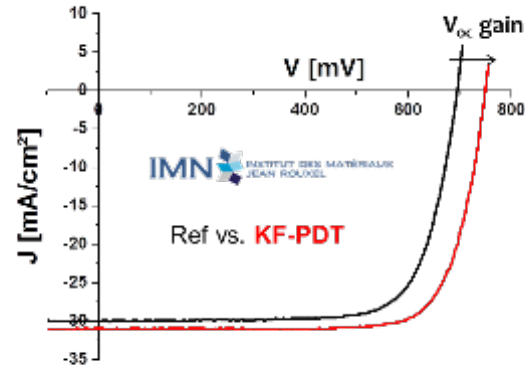
better stability

Matériaux polycristallins : du micro au nano...

Cellules solaires à base de CIGSe



Cross sectional SEM view of a typical CIGSe-based TF solar cell



20 % cell efficiency thanks to KF-PDT
(PhD of Thomas Lepetit)

Objectif: cellules solaires grand gap à base de CIGS (purs sulfures)

Problématiques abordées:

- Corrélation de procédés de croissance par co-évaporation aux propriétés physico-chimiques des couches minces
- influence sur les performances de cellules

Nicolas Barreau et al.



UNIVERSITÉ DE NANTES



Apport des nanos au photovoltaïque

1. Nanostructuration pour le piégeage optique,
la gestion de la couleur et le refroidissement thermique
[surface]
2. Nanomatériaux
[volume]
3. Caractérisation à l'échelle nanométrique
[surface et volume]

Plateforme de cathodoluminescence (CL) et CL résolue en temps

S. Collin et al., C2N

Une plateforme quasiment unique au monde

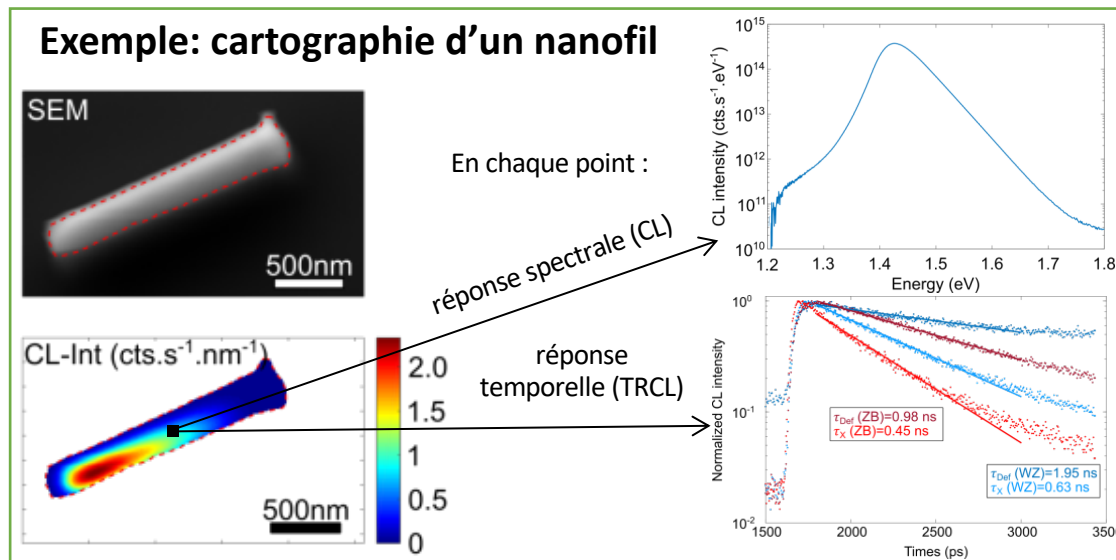
- CL *quantitative*, SEM et EBIC
- CL *résolue en temps*

$\lambda = 250 \text{ nm à } 1.7 \text{ }\mu\text{m}$

Résolution spatiale $< 10 \text{ nm}$

$T = 10\text{K à } 300\text{K}$

Résolution temporelle $\tau \rightarrow 10 \text{ ps}$



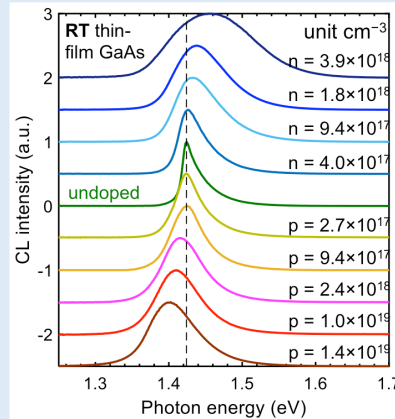
Highlight: measuring the (effective) doping at the nanoscale

S. Collin et al., C2N

Determination of electron/hole concentration using cathodoluminescence:
a contactless, non-destructive, quantitative method with a nanoscale resolution

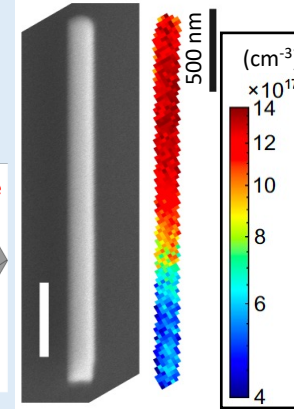
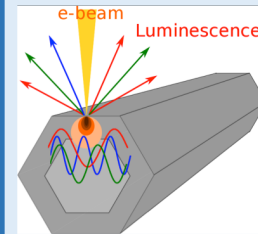
(1) The luminescence spectra contain the signature of doping (bandgap narrowing, broadening, increase of the electron Fermi level).

Reference thin films



(2) The doping is measured in single GaAs:Si and GaAs:Be nanowires.

Mapping of the hole concentration in a GaAs:Be nanowire



The effective doping is assessed for each pixel.

References:

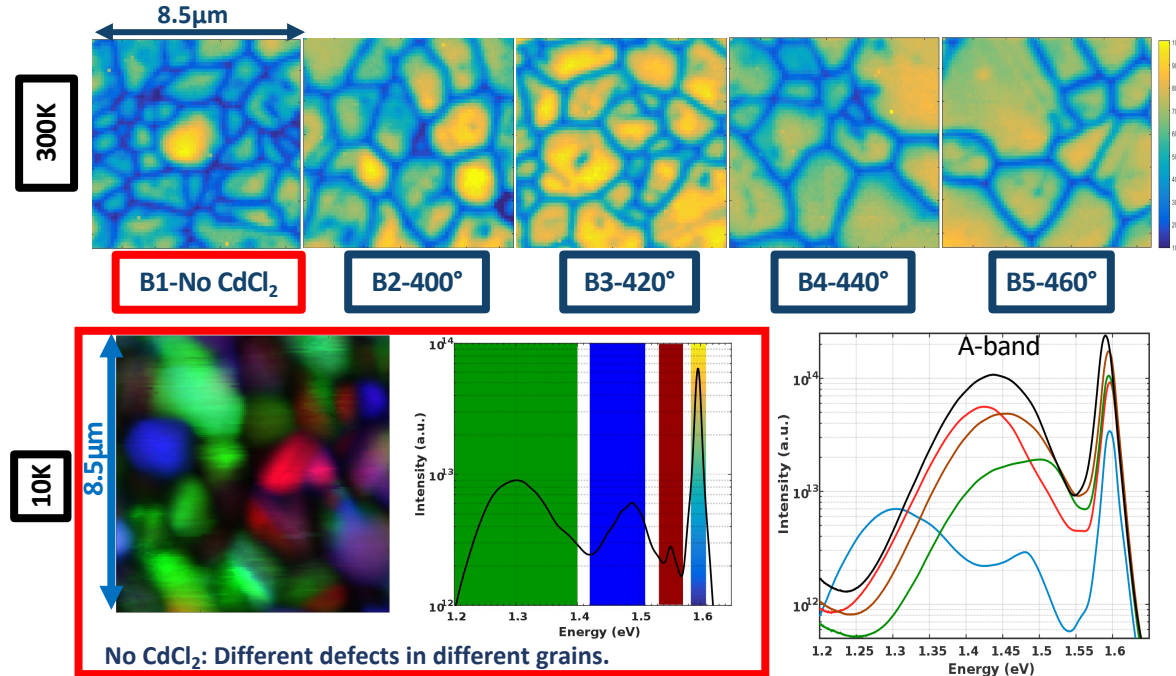
1. Quantitative Assessment of Carrier Density by Cathodoluminescence. I. GaAs thin films and modeling, **Phys. Rev. Applied** 15, 024006 (2021)
2. Quantitative Assessment of Carrier Density by Cathodoluminescence. II. GaAs nanowires, **Phys. Rev. Applied** 15, 024007 (2021)

And also our first proof of concept in **Nano Letters** 17, 6667 (2017)

Investigating bulk defects and recombination at grain boundaries

T. Bidaud, S. Collin et al., C2N
Collab. NREL

CdTe thin films annealed: effect of the CdCl_2 temperature

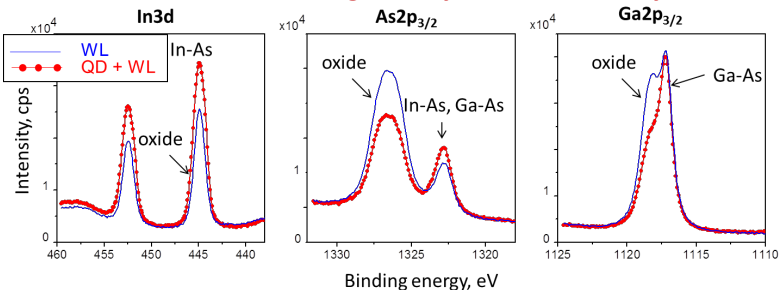


Phys. Rev. Materials 5, 064601, 2021.

Nanoscale chemical analyses and nanoscale wet chemical engineering of III-V based materials and structures

Quantum dots (QDs) ¹ InAs QDs grown on GaAs substrate

Accurate chemical diagnosis by XPS surface analyses

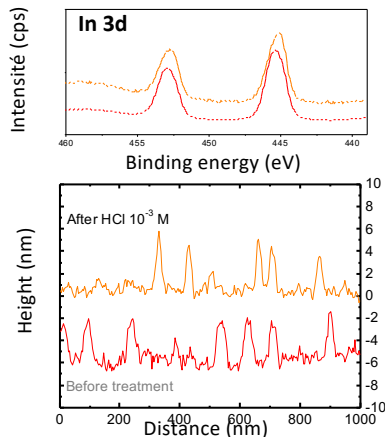
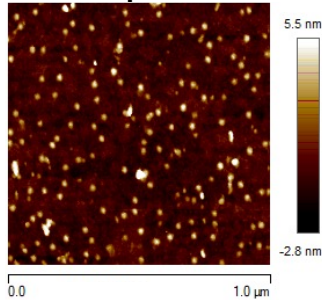


Muriel Bouttemy, Damien Aureau et al. (ILV)

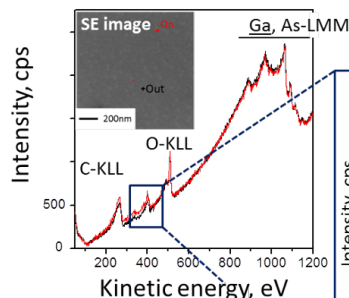
Le XPS et le nano-Auger sont des techniques complémentaires de caractérisation chimiques, parfaitement adaptées aux dimension de nano-structures (profondeur sondée 5-10 nm et taille de spot allant de 600µm en XPS à 12 nm pour l'Auger) et qui donnent également accès à la chimie des interfaces (abrasion ionique).

QDs shape and size modulation (bandgap tuning)

AFM map



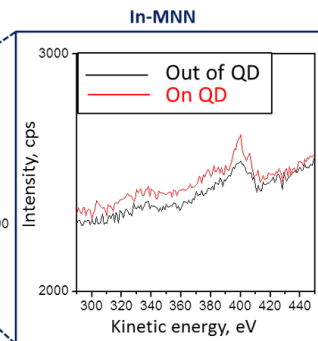
Auger widescan



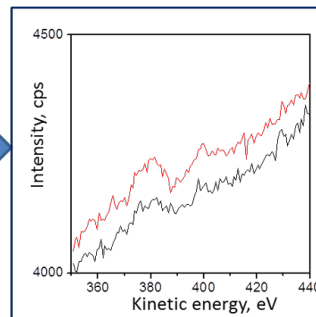
Nano-Auger local chemical characterization

(20 kV-10 nA- ~12 nm spot size)

Evidence of maintaining QDs
→ Precise nano-etching: QDs thinning
by iterating deoxidation cycle



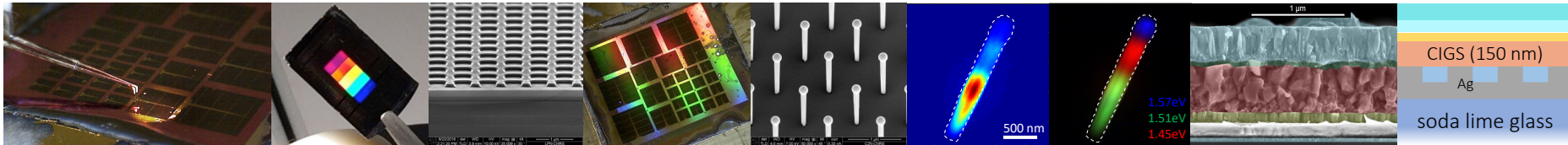
1st cycle 10⁻² M (1min)



2nd cycle 10⁻² M (1min)

Conclusion

1. Nanostructuration pour le piégeage optique,
la gestion de la couleur et le refroidissement thermique
[surface]
2. Nanomatériaux
[volume]
3. Caractérisation à l'échelle nanométrique
[surface et volume]



Merci pour votre attention !

1. Nanostructuration pour le piégeage optique,
la gestion de la couleur et le refroidissement thermique
[surface]
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[volume]
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[surface et volume]

