FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR
UNINOVA CEMOP Centre of Excellence in Microelectronics, Optoelectronics and Processes
CENIMAT Centro de Investigação de Materiais
i3N Instituto de Nanoestruturas, Nanomodelação e Nanofabricação
LNEG Laboratório Nacional de Energia e Geologia, I. P.

AltaLuz

ALTA EFICIÊNCIA EM CÉLULAS SOLARES TANDEM DE FILME FINO USANDO COMBINAÇÕES DE MATERIAIS E ESTRUTURAS NANOFOTÓNICAS DE CAPTAÇÃO DE LUZ

High Efficient Wafer-free Tandem Solar Cells via Combined Materials and NanoPhotonic Light Trapping

(1) M. J. MENDES, O. SANCHEZ, A. ARAÚJO, A. VICENTE, A. LYUBCHYK, T. MATEUS, H. ÁGUAS, E. FORTUNATO AND **R. MARTINS (PI)**

(2) F. NEVES, J. MASCARENHAS, A. BARREIROS, M. J. BRITES, B. CORREIA, **A. JOYCE**

AltaLuz - KickOff
31 May 2016

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(2) LNEG, Laboratório Nacional de Energia e Geologia, Estrada do Paço do Lumiar, 22, 1649-038 Lisboa

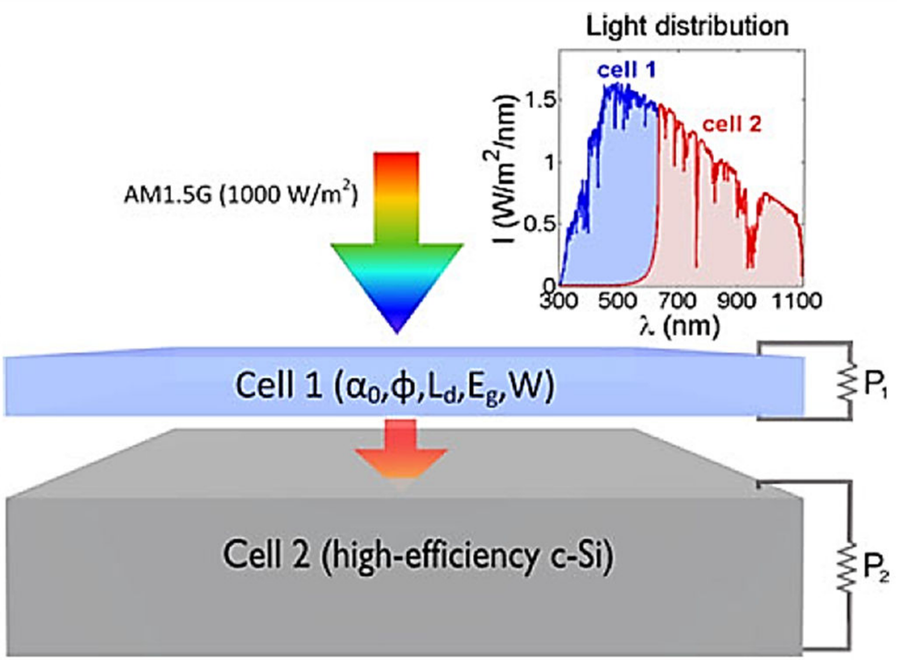
The Partners

UNINOVA
CEMOP
Centre of Excellence in Microelectronics, Optoelectronics and Processes

CENIMAT
CENTRO DE INVESTIGAÇÃO DE MATERIAIS
i3N
INSTITUTO DE NANOESTRUTURAS, NANOMODELAÇÃO E NANOFABRICAÇÃO
INVESTIGAÇÃO, INOVAÇÃO E APLICAÇÕES DE ENGENHARIA

LNEG
Laboratório Nacional de Energia e Geologia, I. P.

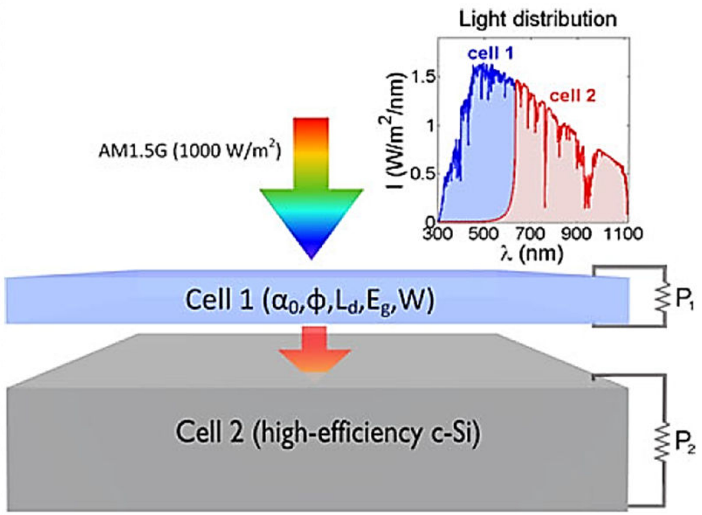
The concept → 4-T double-junctions

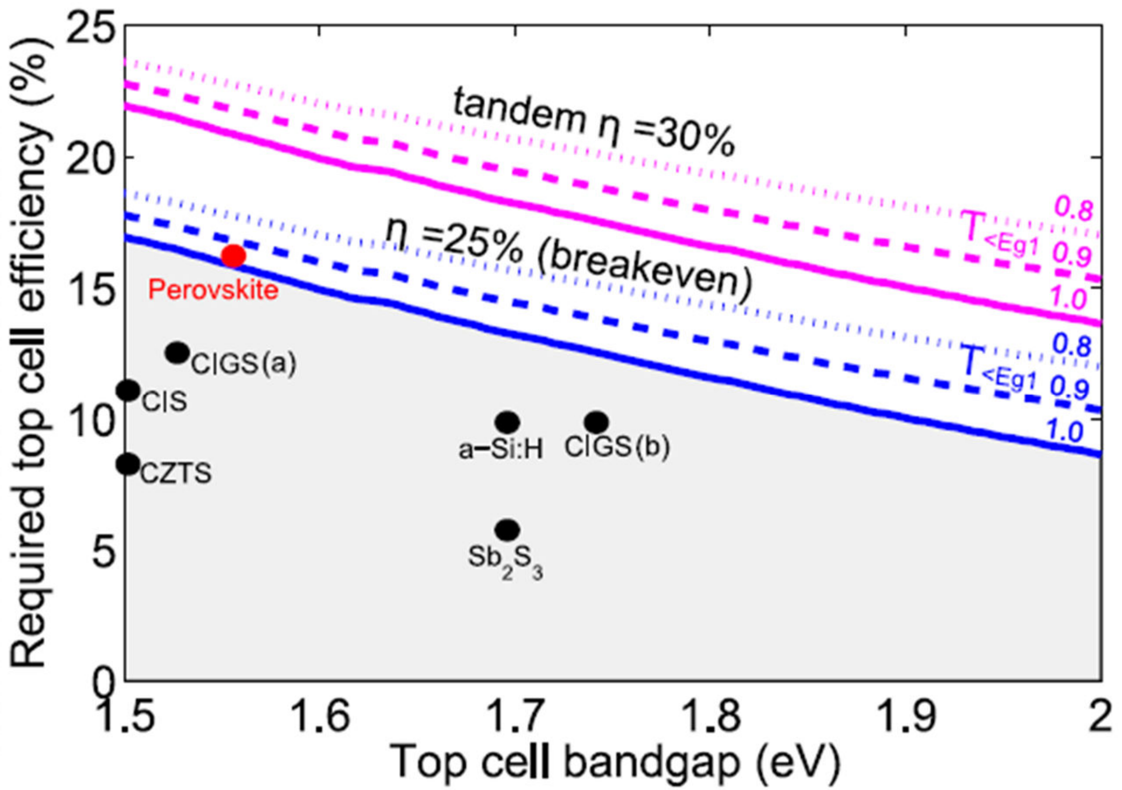


T. P. White et al. IEEE PV (2014)

1) No current matching required
2) No lattice matching required
3) Distinct materials can be used for subcells. **Big number of possible combinations!**
4) Subcells optimized independently (e.g. in distinct labs) to get the most out of each
5) Facilitates implementation of **light management structures**
6) Allows better performance (**adaptability**) with changing illumination spectrum

The concept - 4-T double-junctions





N. N. Lal et al. IEEE PV (2014)

Efficiencies > 25% are feasible with current technology

Scientific Novelties of AltaLuz

1) Device simulation - Optimization of module design for 4-terminal integration

2) Light trapping – combination of photonic structures for spectral matching and absorption enhancement

3) Top cell:

- Application of light trapping in Perovskites
- Kesterite cells fabricated by powder ball milling (*non-vacuum, high-throughput*)

4) Bottom cell – Thin film mc-Si cell (instead of conventional c-Si wafer)

5) Stacking technology:

- Mechanical attachment vs. Conformal deposition
- Innovative interlayers and optical coupling with intermediate TCOs

1) Device Simulation – LNEG

- Software: **Matlab/Simulink**
  - Simulation of the response of each individual sub-cell
  - Simulation of the 4-T tandem
  - Design of module circuitry (electronics)
  - Optimization of cells areas and module architecture

IEEE J. ELECTRON DEVICES SOCIETY, 1, NO. 6, 2013

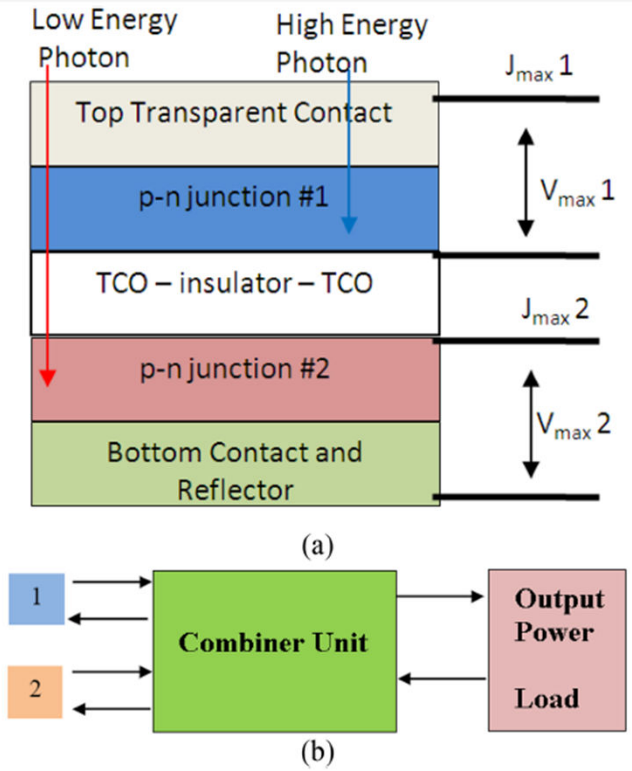


Fig. 7. (a) Schematic of the proposed two-junction four-terminal solar cell. (b) External electric circuitry to combine the electricity generated separately by the two junctions.

1) Device Simulation – Recent literature

$CH_3NH_3PbI_3$ perovskite / silicon tandem solar cells: characterization based optical simulations

Miha Filipič,[1,*] Philipp Löper,[2] Bjoern Niesen,[2] Stefaan De Wolf,[2] Janez Krč,[1] Christophe Ballif,[2] and Marko Topič[1]

[1] University of Ljubljana, Faculty of Electrical Engineering, Tržaška 25, SI-1000 Ljubljana, Slovenia
[2] Ecole Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Photovoltaics and Thin-Film Electronics Laboratory, Maladière 71, CH-2000 Neuchâtel, Switzerland

6 Apr 2015 | Vol. 23, No. 7 | DOI:10.1364/OE.23.00A263 | OPTICS EXPRESS A264

- Full simulation and top layers **optimization:**
  - c-Si HiT wafer + Perovskite
  - 4-terminal and 2-terminal Tandems
  - With & without texturing

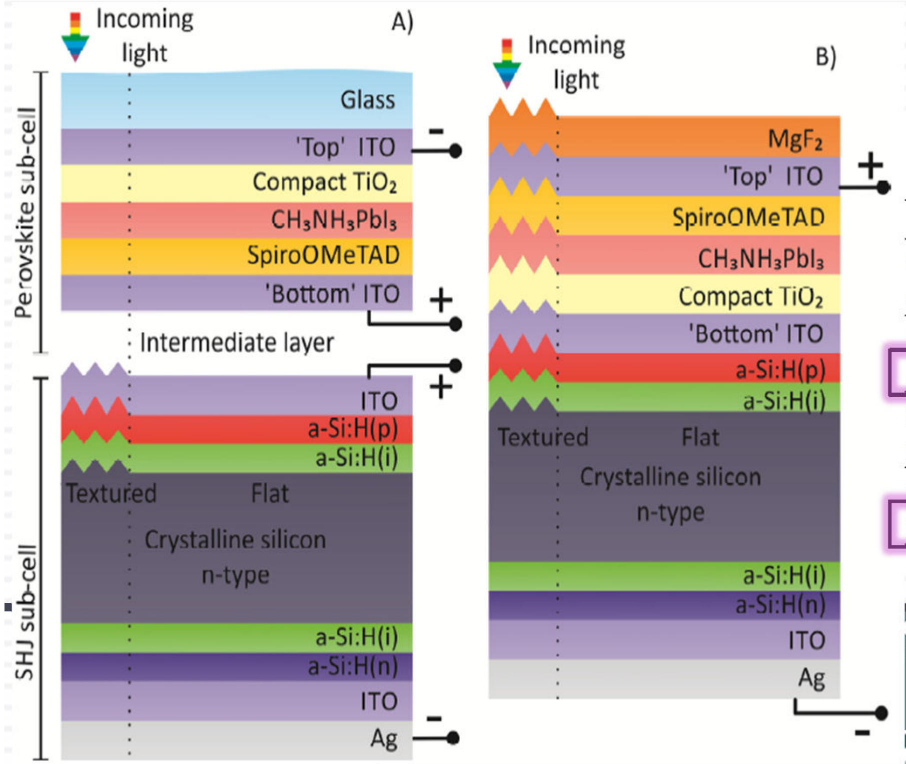


Table 6. Estimated efficiencies of various four-terminal (4T) and two-terminal (2T) tandem configurations based on the one-diode model and simulated J_{sc} values.

	Perovskite cell (%)	SHJ cell (%)	Tandem cell (%)
4T Constrained Flat	16.4	11.1	27.5
4T Unconstrained Flat	19.2	9.8	29.1
4T Constrained Textured	16.3	12.1	28.4
4T Unconstrained Textured	19.2	11.0	30.1
2T Constrained Flat	14.5	10.9	25.4
2T Unconstrained Flat	17.3	12.9	30.2
2T Constrained Textured	15.2	11.7	26.8
2T Unconstrained Textured	17.5	12.8	30.3

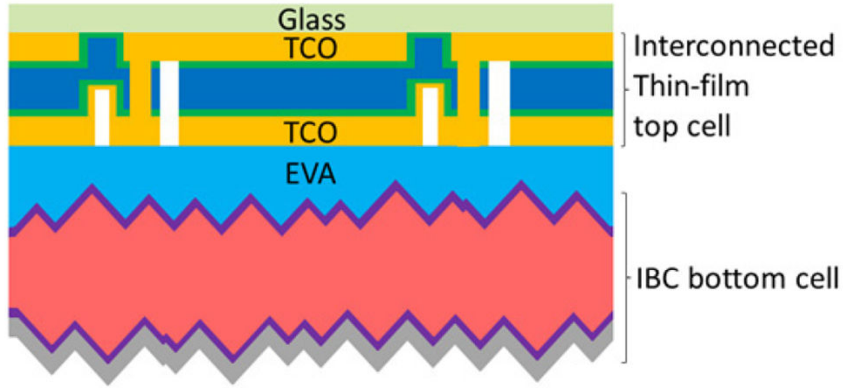
1) Device Simulation – Recent literature

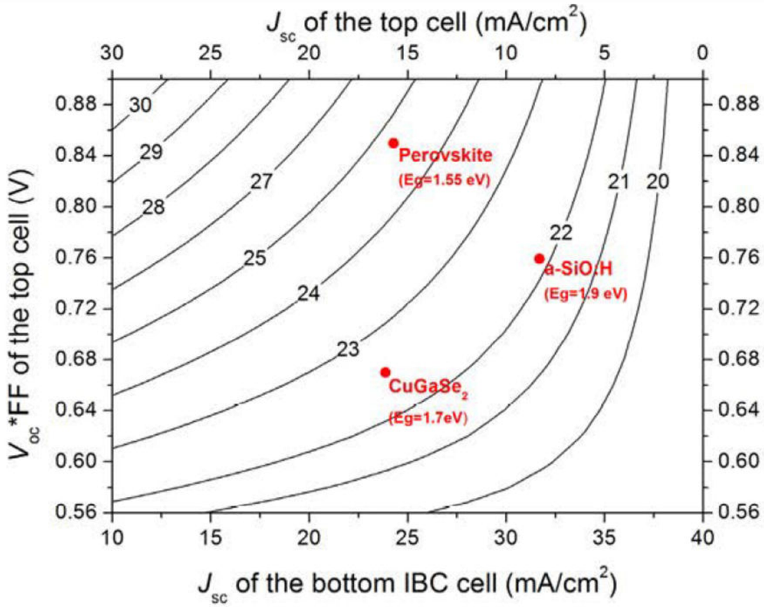
5th International Conference on Silicon Photovoltaics, SiliconPV 2015

Design of 4-terminal solar modules combining thin-film wide-bandgap top cells and c-Si bottom cells

Dong Zhang[a,*], Wim Soppe[a], Ruud. E. I. Schropp[a,b]

[a]ECN-Solliance, High Tech Campus 21, 5656 AE Eindhoven, the Netherlands
[b]TU/e-Solliance, Department of Applied Physics, PMP, P.O.Box 513, 5600 MB Eindhoven, the Netherlan

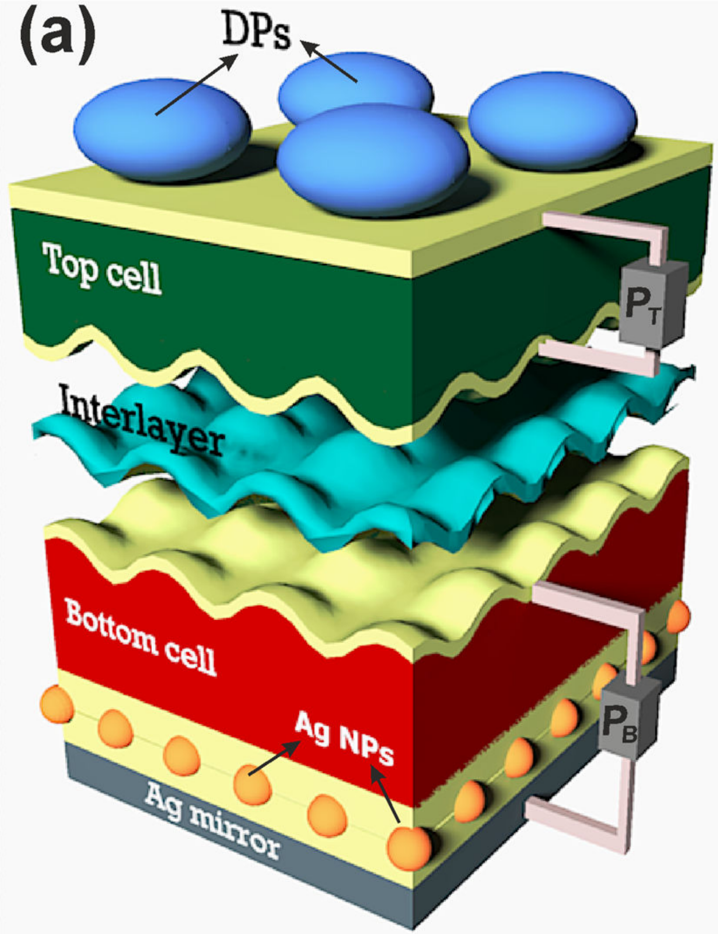


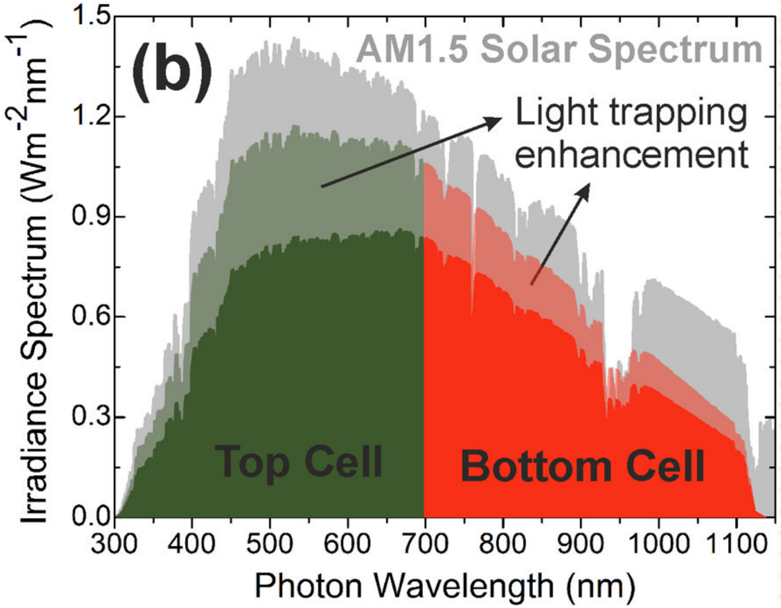


	a-SiO:H	$CuGaSe_2$	Perovskite
V_{oc} (V)	1.042	0.921	1.13
FF	0.73	0.73	0.75
V_{oc}*FF (V)	0.76	0.67	0.85
J_{sc} (mA/cm²)	8.26	16.16	15.78

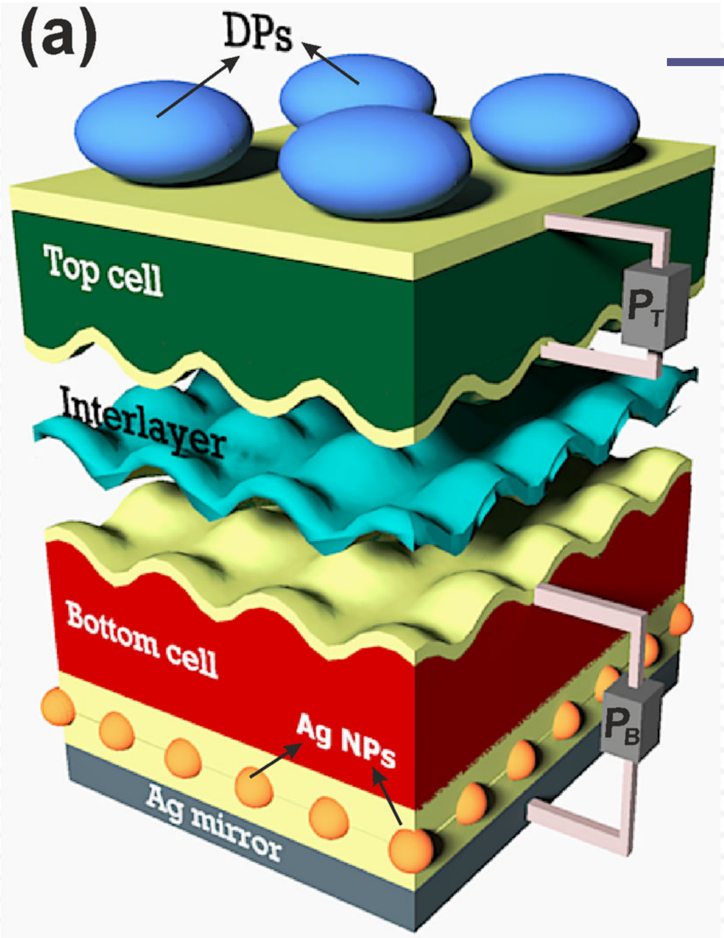
- **3 types of top cells** tested on an IBC c-Si wafer as bottom cell
- Architecture has series-interconnected top cells with optimum area

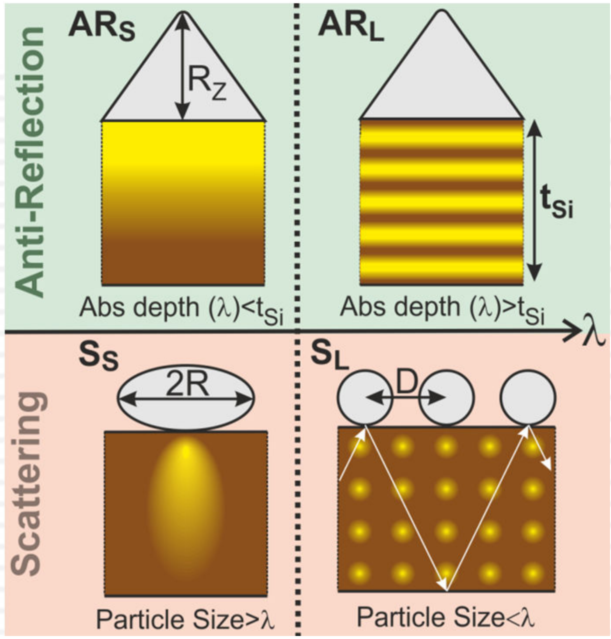
2) Light Trapping – CENIMAT/UNINOVA

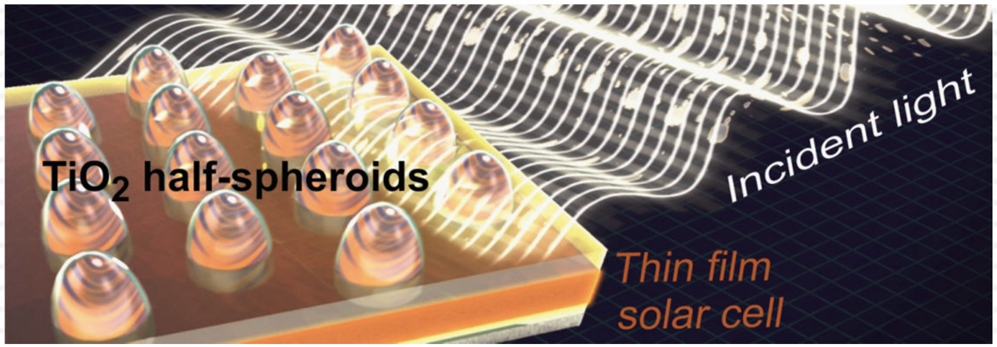




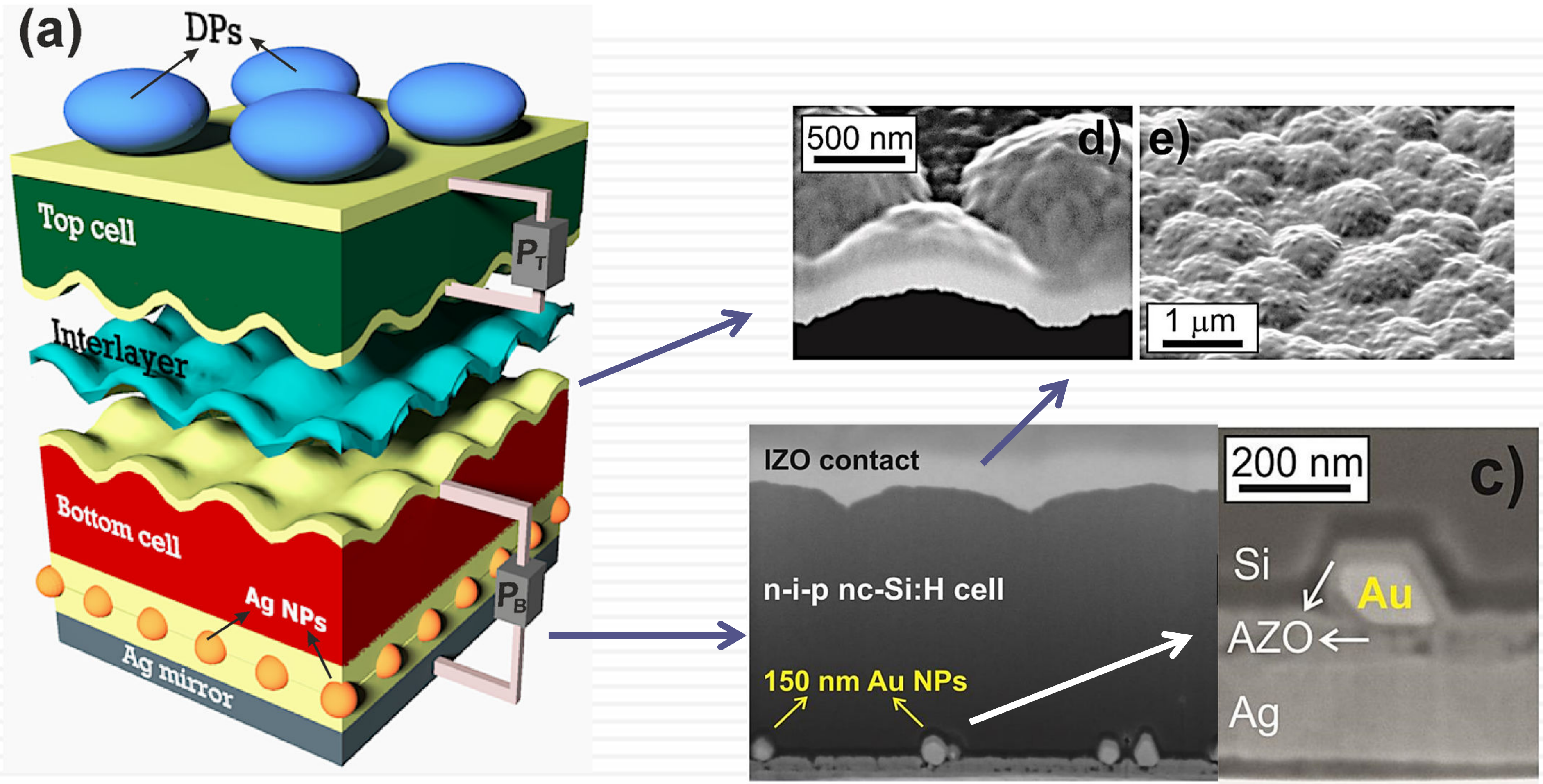
2) Light Trapping – Front structures





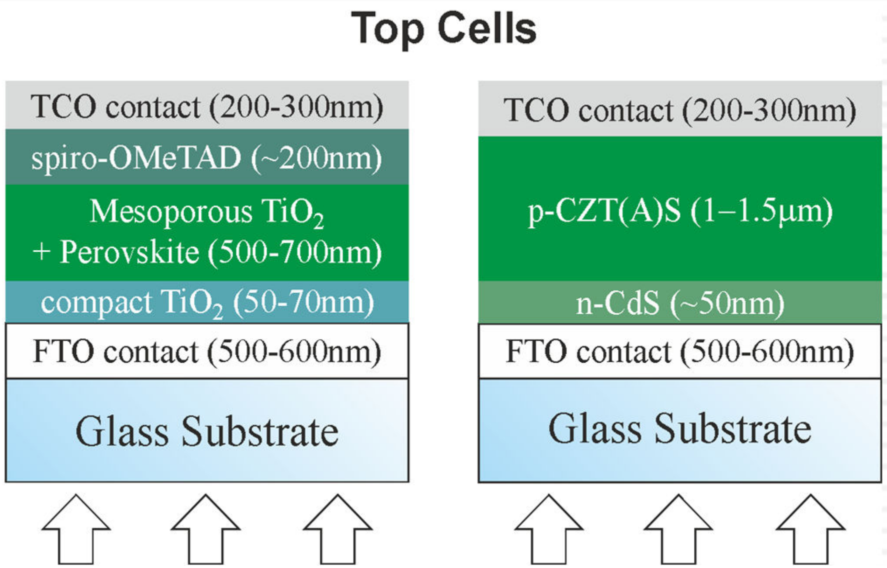


2) Light Trapping – Rear structures



3) Top Cells – LNEG

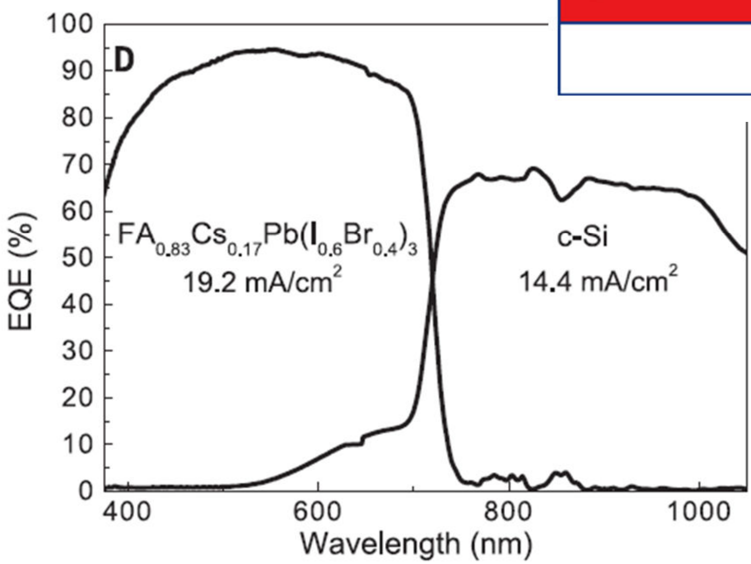
- <u>Main breakthroughs</u>:
  - **Perovskites** – light trapping implementation on frontal surface
  - **Kesterites** – new material for tandem with Si (bandgap optimization will be challenging)



3) Top Cells – Recent literature

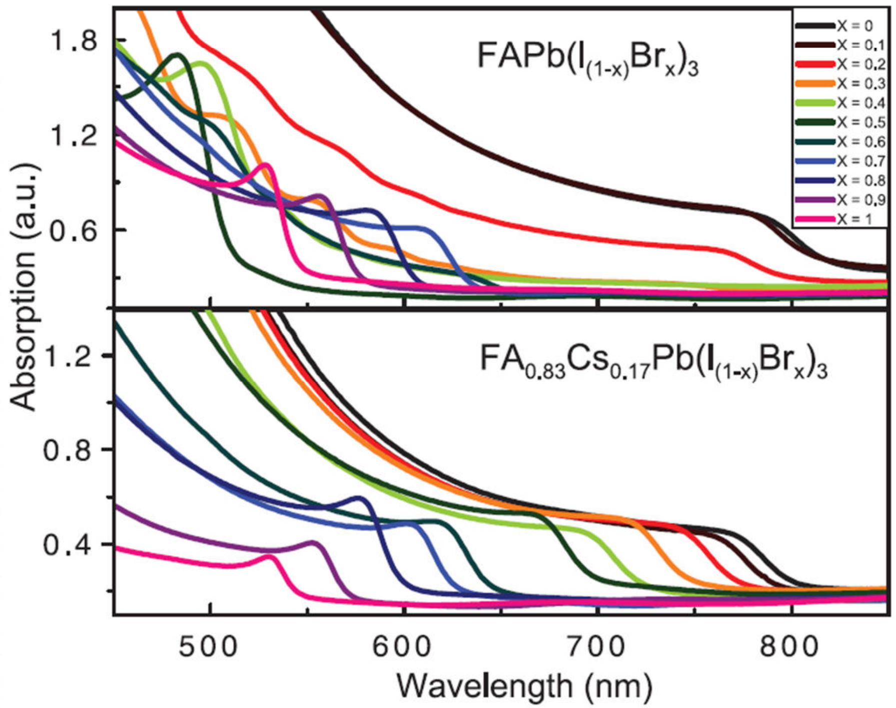
A mixed-cation lead mixed-halide perovskite absorber for tandem solar cells
David P. McMeekin, Golnaz Sadoughi, Waqaas Rehman, Giles E. Eperon, Michael Saliba, Maximilian T. Hörantner, Amir Haghighirad, Nobuya Sakai, Lars Korte, Bernd Rech, Michael B. Johnston, Laura M. Herz and Henry J. Snaith (January 7, 2016) *Science* **351** (6269), 151-155. [doi: 10.1126/science.aad5845]

Science AAAS



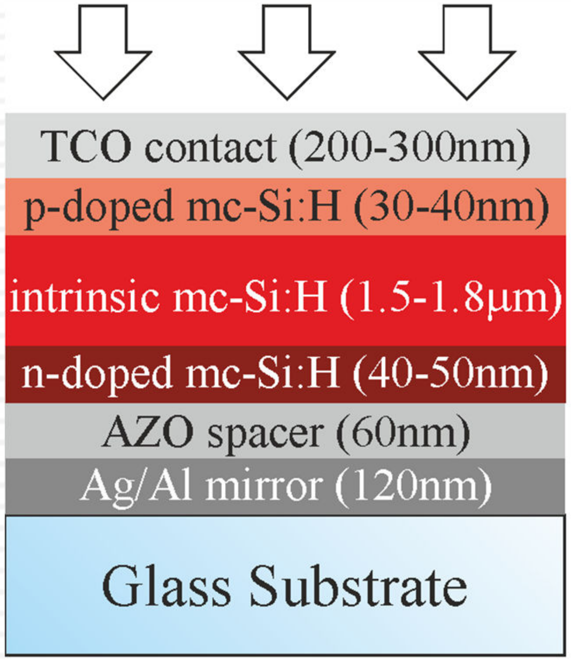
Ideal Perovskite for top cell on Si:
Eg~1.74 eV

$[HC(NH_2)_2]_{0.83}Cs_{0.17}Pb(I_{0.6}Br_{0.4})_3$

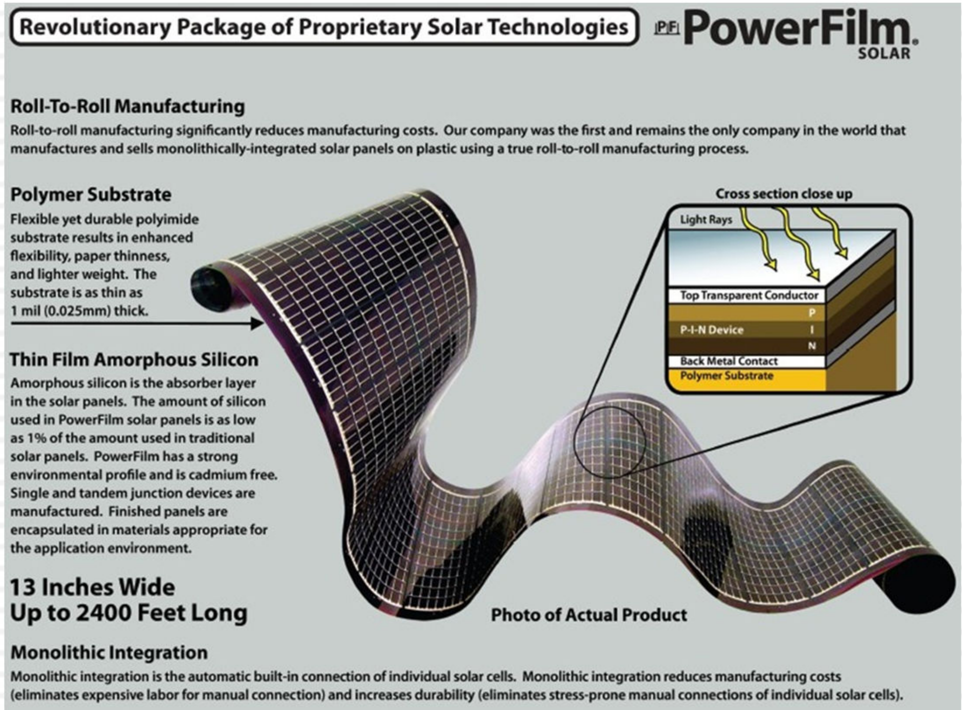


4) Bottom Cell – UNINOVA/CENIMAT

- Main novelty – thin film Si bottom cell

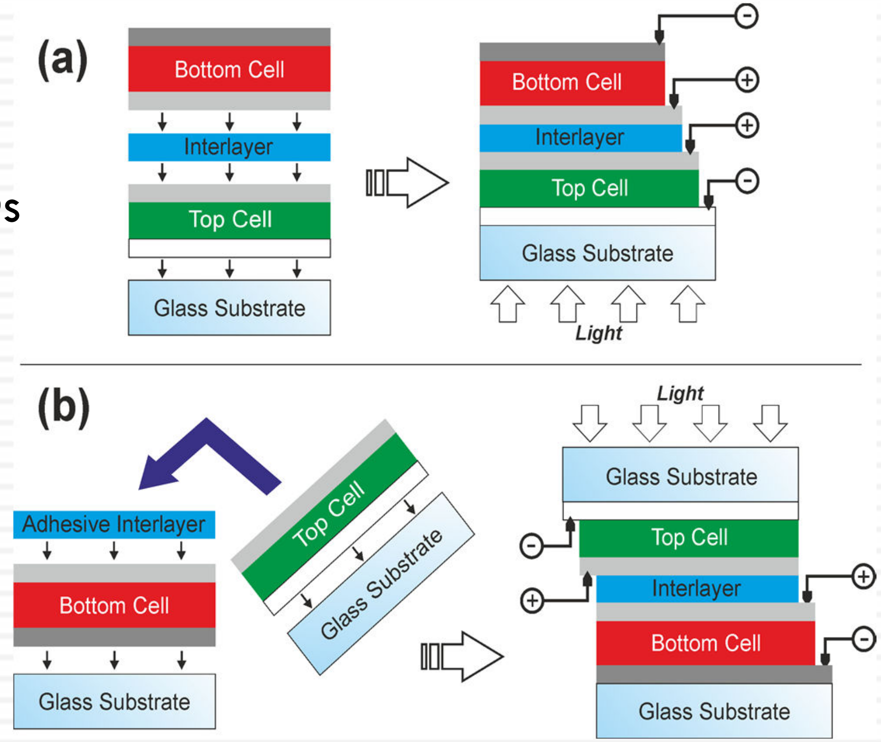


Bottom Cell



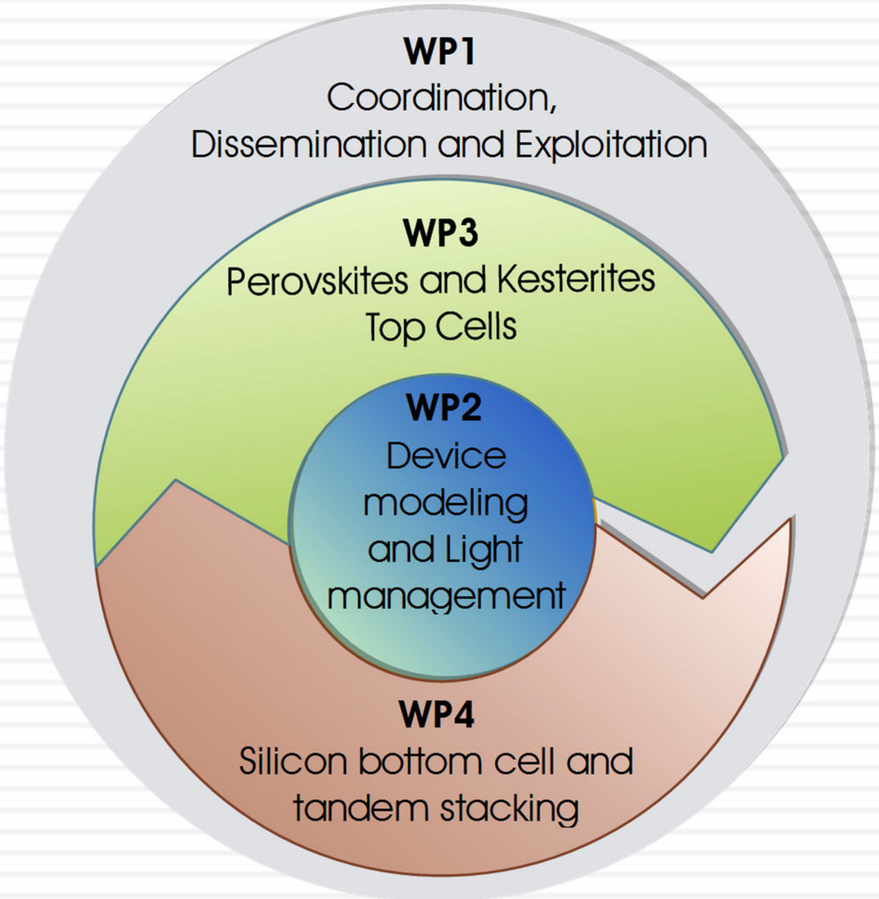
5) Stacking technology – Interlayer

- **Interlayer:**
  - Electrically insulating
  - Transparent to top cell sub-bandgap light
  - Optically matched with intermediate TCOs

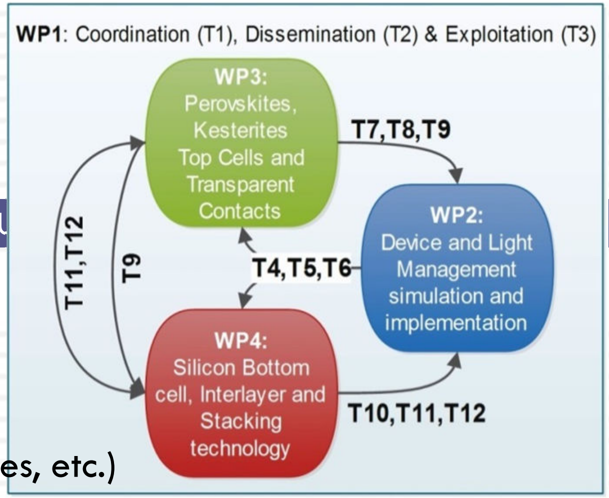


- **2 Stacking approaches:**
  - <u>Interlayer for **A – UNINOVA:**</u> physically-deposited SiO_X or SiC_X film, in which *x* is adjusted to tune the refractive index (*N*)
  - <u>Interlayer for **B – LNEG:**</u> adhesive polymer, with *N* adjusted by embedding TiO_2 nanoparticles at the appropriate concentration

Project Management



WP1 Activities



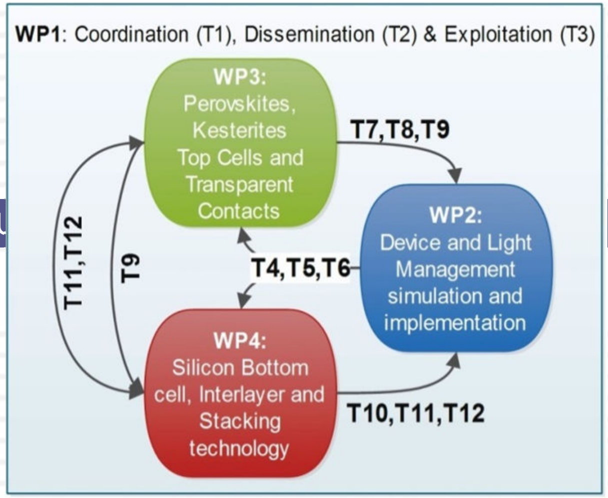
- **WP1 - Coordination, Dissemination and Exploitation**

  - **<u>T1 – Project Management</u> (UNINOVA) – M0-M36**
    - T1.1 – Communication Management (Reports to FCT, publications, conferences, etc.)
    - T1.2 – Organization of Meetings (at least <u>1 per year</u> – *in May*?)
    - T1.3 - Data Management, Monitoring of Project Activities and Reporting
    - T1.4 - Legal, Financial and Administrative Management
    - T1.5 - Quality and Risk Assessment Management

  - **<u>T2 – Communication & Dissemination</u> (CENIMAT) – M5-M36**
    - Website update (<u>http://sites.fct.unl.pt/altaluz</u> , <u>*User=al/Pass=pv*</u>) → *Let's make public?* - M. J. Mendes
    - Peer-reviewed publications
    - Workshops and conferences (e.g. *Jornadas CENIMAT* - <u>http://eventos.fct.unl.pt/jornadascenimat/</u>)
    - Open days and summer schools (e.g. *Ciência Viva* in 11-15 July)

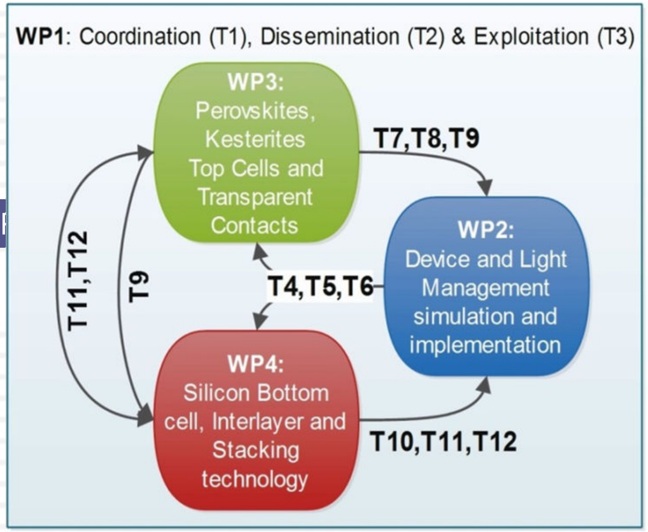
  - **<u>T3 - IPR Promotion and Exploitation Management</u> (LNEG) – M12-M36**
    - T3.1 - IPR Promotion and Innovation Management
    - T3.2 - Exploitation Plan & Technology Transfer

WP2 Activities



- **WP2 - Device Simulation and Light management**
  - **T4 – Modelling 4-terminal double-junction architecture** (LNEG) – M0-M18
    - Simulation of individual sub-cells (both top and bottom separately)
    - Simulation of tandem cells (top + bottom)
    - Simulation of complete module circuitry
    - Optimization of module architecture and cell parameters
  - **T5 – Light trapping simulation and optimization** (CENIMAT) – M0-M24
    - Optimization of light trapping structures (Dielectric semi-prolates and PBRs) for individual bottom cells
    - Optimization of optical structures for the tandem device (Dielectric in front and PBRs in rear)
    - Optimization of complete device using optical (FDTD) + electrical (FEM) simulations with Lumerical
  - **T6 - Implementation of light trapping structures** (CENIMAT) – M7-M35
    - Dielectric semi-prolates - Colloidal Lithography and possibly Nano-imprint (stamping)
    - Plasmonic back reflectors (PBRs) – thin film annealing and possibly colloidal self-assembly with Ag NPs

WP3 Activities



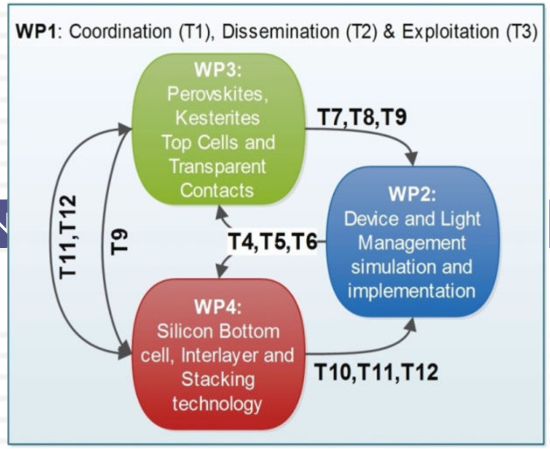
- **WP3 - Perovskites and Kesterites Top cells**

- **<u>T7 – Perovskite top cell</u> (LNEG) – M0-M30**
  - Achievement of high-bandgap (>1.7 eV) Perovskite material (with Cs?)
  - Achievement of high-bandgap (>1.7 eV) Perovskite solar cell
  - Implementation of light trapping (Dielectric semi-prolates by colloidal lithography)
  - Integration of Perovskite solar cell in tandem device

- **<u>T8 – Kesterite top cell</u> (LNEG) – M0-M30**
  - Achievement of high-bandgap (>1.8 eV) Kesterite material (with Sb?) via powder milling
  - Achievement of high-bandgap (>1.8 eV) Kesterite solar cell
  - Integration of Kesterite solar cell in tandem device (*possibly with light trapping)*

- **<u>T9 – Transparent Electrodes</u> (UNINOVA) – M6-M34**
  - Investigation of best properties of front and intermediate TCOs (similar *N* to avoid reflections)
  - Fabrication and characterization of optimized TCOs and optical coupling with interlayer

WP4 Activities



- **WP4 - Silicon Bottom cell and Tandem integration**

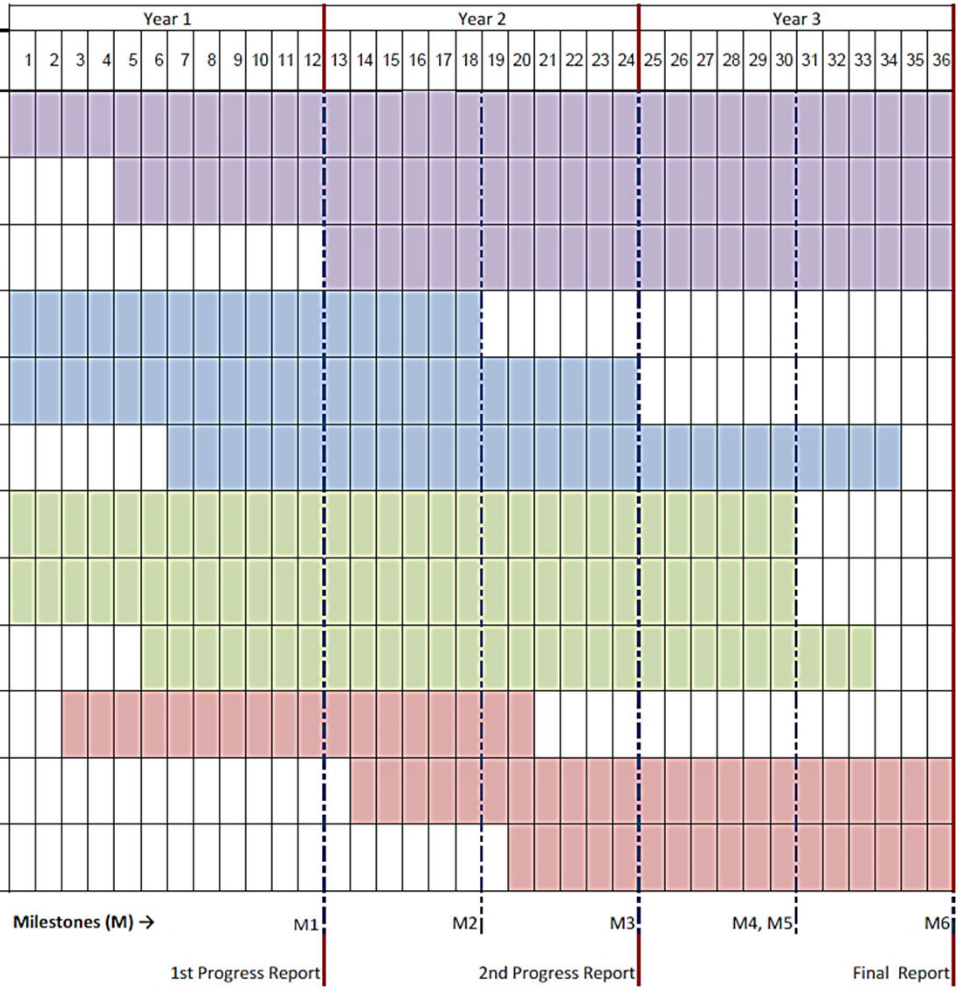
- **<u>T10 – Microcrytalline Silicon bottom cell</u> (UNINOVA) – M3-M21**
  - High efficient mc-Si:H n-i-p and p-i-n cells for operation under red-NIR illumination (λ~700-1200 nm)
  - Implementation of light trapping (Ag NPs PBRs by thin film annealing and colloidal self-assembly)
  - Integration of mc-Si:H solar cells in tandem device

- **<u>T11 – Intermediate layer optimization</u> (LNEG) – M13-M36**
  - Investigation of best optical properties for the interlayers of both approaches
  - Interlayer A - ~50nm-thick SiO_x or SiC_x layer, deposited on the rear surface of the top cell
  - Interlayer B - adhesive transparent polymer (e.g. epoxy deposited by spin-coating to form a thin film)

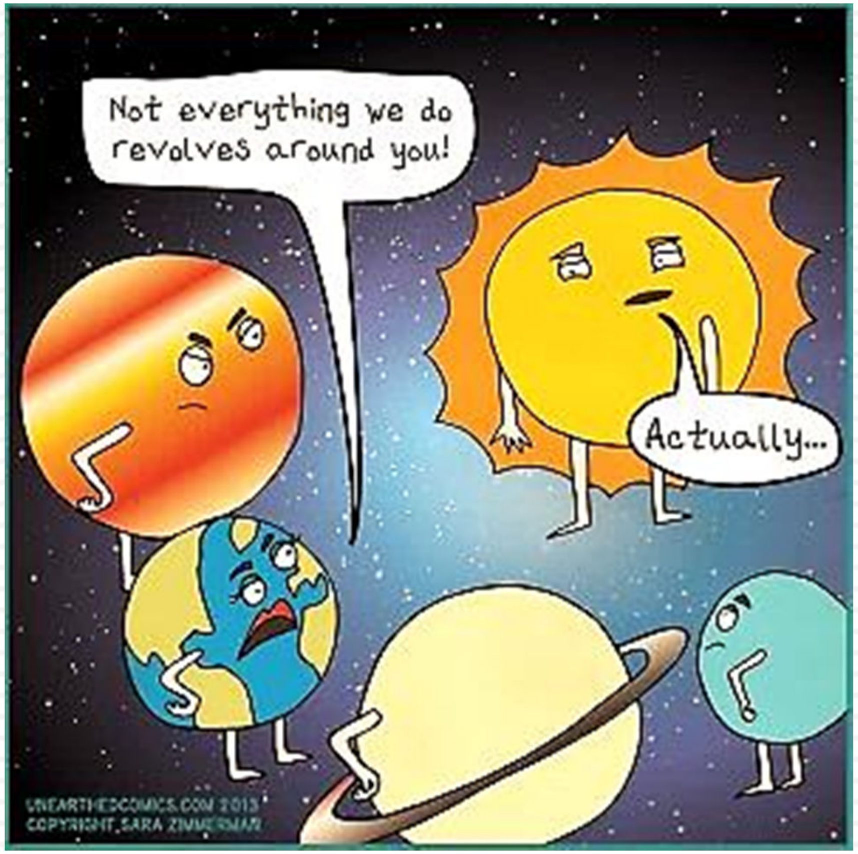
- **<u>T12 – Stacking 4-terminal tandem cells</u> (UNINOVA) – M20-M36**
  - Approach A – conformal growth of bottom cell on a top cell (both superstrate-type)
  - Approach B – mechanical stacking of substrate-type bottom-cell and superstrate-type top-cell
  - <u>Fabrication of 4-terminal test modules with optimized simulated design</u>

Timeline

Work Package	Task Nº	Task Denomination	Person*month	Participant responsible for task	Acronyms of partners involved in task
1	1	Project management	13,00	UNINOVA	CENIMAT, LNEG
	2	Communication and Dissemination	15,00	CENIMAT	UNINOVA, LNEG
	3	IPR Promotion and Exploitation Management	9,00	LNEG	UNINOVA, CENIMAT
2	4	Modelling 4-terminal double-junction architecture	12,00	LNEG	UNINOVA, CENIMAT
	5	Light trapping simulation and optimization	17,00	CENIMAT	UNINOVA, LNEG
	6	Implementation of light trapping structures	25,40	CENIMAT	UNINOVA, LNEG
3	7	Perovskite top cell	23,00	LNEG	UNINOVA, CENIMAT
	8	Kesterite top cell	23,00	LNEG	UNINOVA, CENIMAT
	9	Transparent electrodes	19,00	CENIMAT	UNINOVA, LNEG
4	10	Microcrytalline Silicon bottom cell	15,00	UNINOVA	CENIMAT, LNEG
	11	Intermediate layer optimization	21,00	UNINOVA	CENIMAT, LNEG
	12	Stacking 4-terminal tandem cells	20,00	UNINOVA	CENIMAT, LNEG
		Total:	212,40		



Thank you!



FUNDING:
EU FP7 Marie Curie Action (FP7- PEOPLE-2013-IEF) - DIELECTRIC PV project (Grant No. 629370)
FEDER funds (COMPETE 2020 Program) and Foundation for Science and Technology (FCT-MEC) - **PTDC/CTM-ENE/5125/2014,** UID/CTM/50025/2013, PEst-C/CTM/LA0025/2013-14 and PTDC/CTM-ENE/2514/2012.

EXTRA SLIDES

Activities Planning for first steps

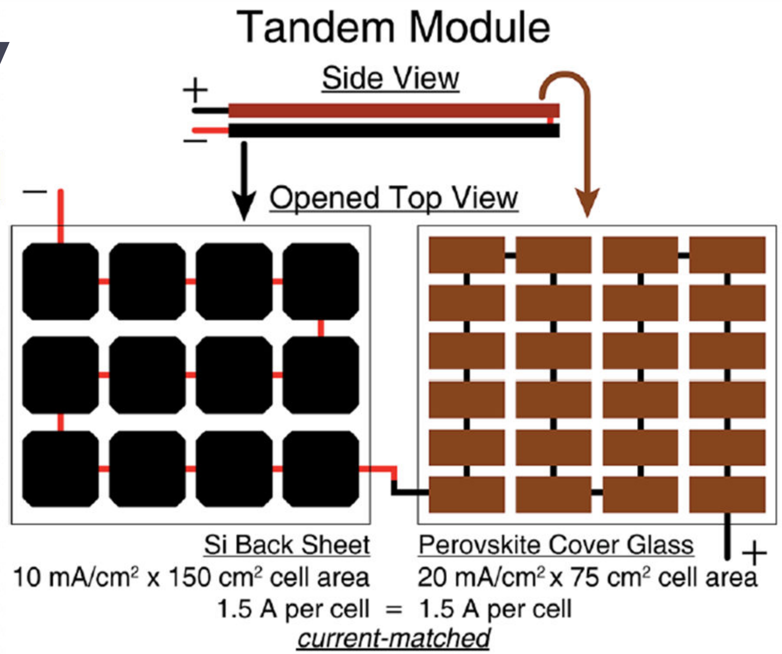
- WP1
  - **T1 – Project Management** (UNINOVA M0-M36) – RM, PM, HA, AJ, …
  - **T2 – Communication & Dissemination** (CENIMAT M5-M36) – PM, HA, MM (LNEG?)
  - **T3 - IPR Promotion and Exploitation** (LNEG M12-M36) – AJ, RM, PM, …
- WP2
  - **T4 – Modelling 4-terminal double-junction** (LNEG M0-M18) – AJ, SH, MM
  - **T5 – Light trapping simulation** (CENIMAT M0-M24) – SH, MM
  - **T6 - Implementation of light trapping** (CENIMAT M7-M35) – OS, UNINOVA BI, MM
- WP3
  - **T7 – Perovskite top cell** (LNEG M0-M30) – MB, JM
  - **T8 – Kesterite top cell** (LNEG M0-M30) – BC, FN
  - **T9 – Transparent Electrodes (UNINOVA M6-M34)** – HA, AV, AL
- WP4
  - **T10 – Microcrytalline Si bottom cell** (UNINOVA M3-M21) – TM, UNINOVA BI
  - **T11 – Intermediate layer optimization** (LNEG M13-M36) – UNINOVA BI, MB, JM, FN
  - **T12 – Stacking 4-terminal tandems** (UNINOVA M20-M36) - ALL

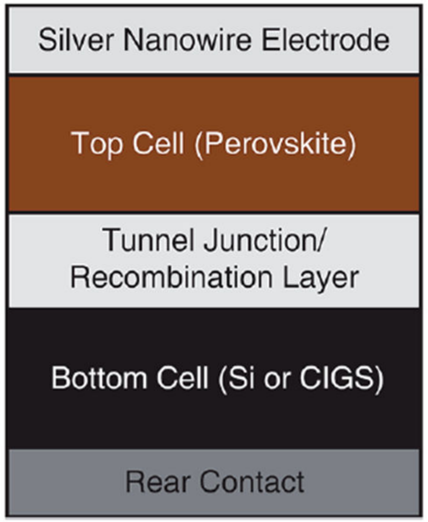
5) Stacking technology

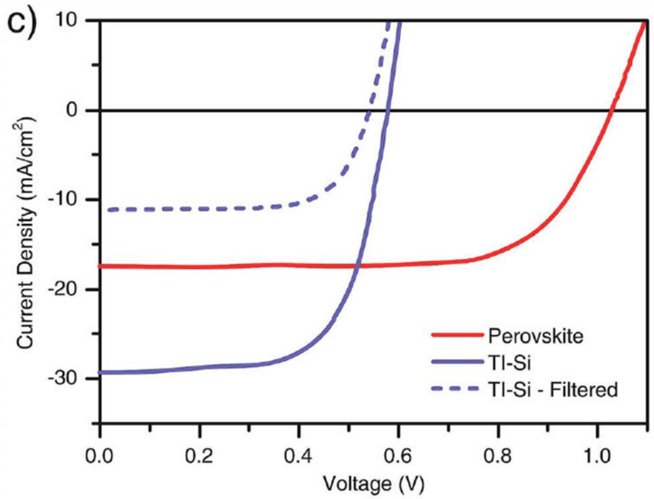
Energy & Environmental Science

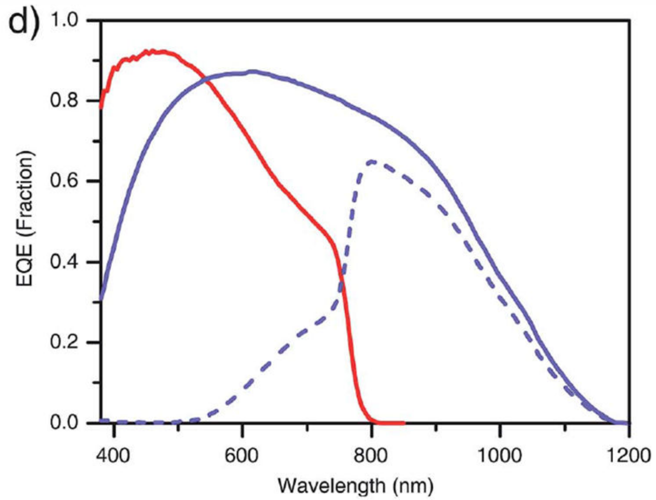
Semi-transparent perovskite solar cells for tandems with silicon and CIGS†

Colin D. Bailie,‡[a] M. Greyson Christoforo,‡[b] Jonathan P. Mailoa,[c] Andrea R. Bowring,[a] Eva L. Unger,[a] William H. Nguyen,[d] Julian Burschka,§[e] Norman Pellet,[e] Jungwoo Z. Lee,[c] Michael Grätzel,[e] Rommel Noufi,[f] Tonio Buonassisi,[c] Alberto Salleo[a] and Michael D. McGehee*[a]



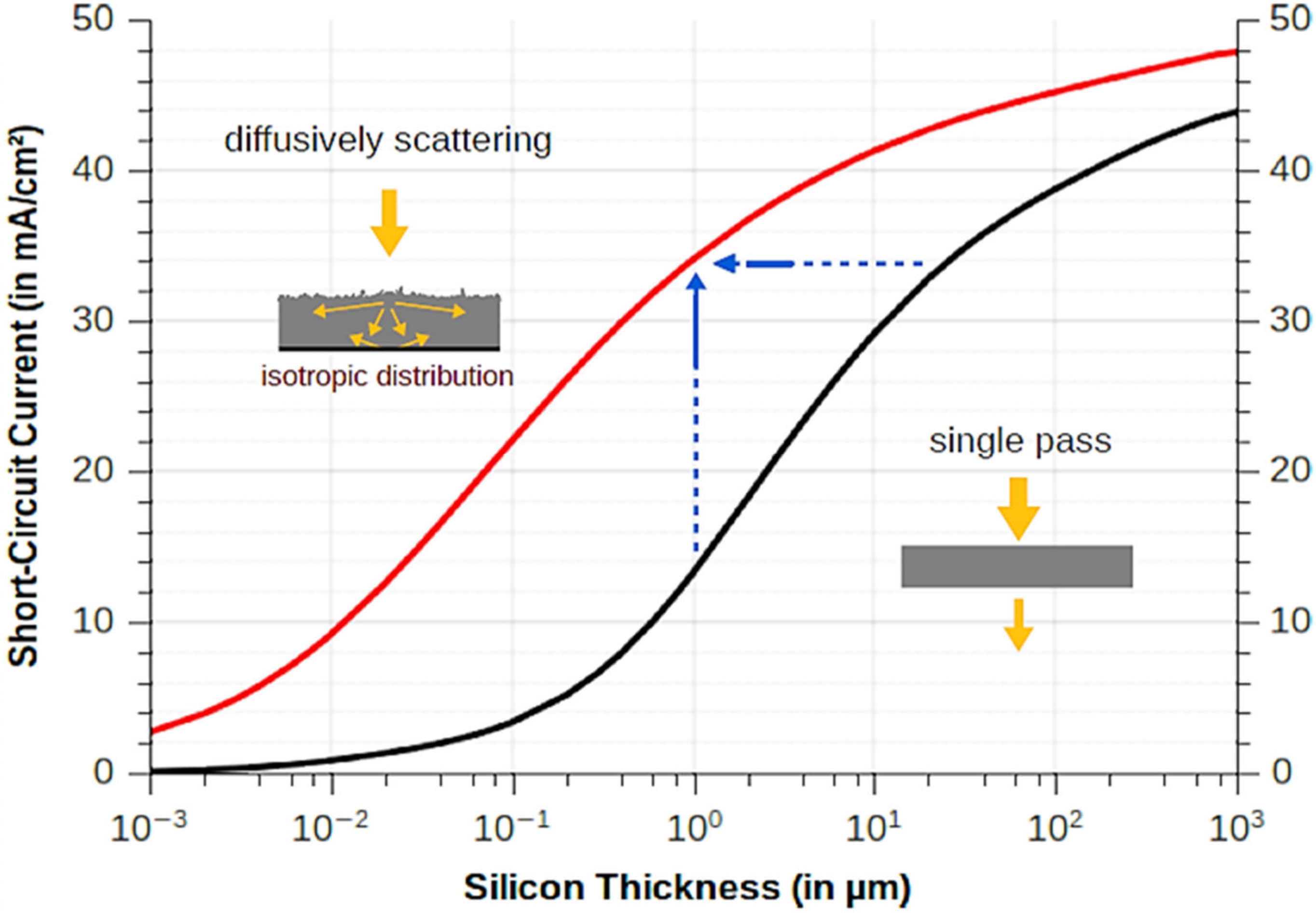




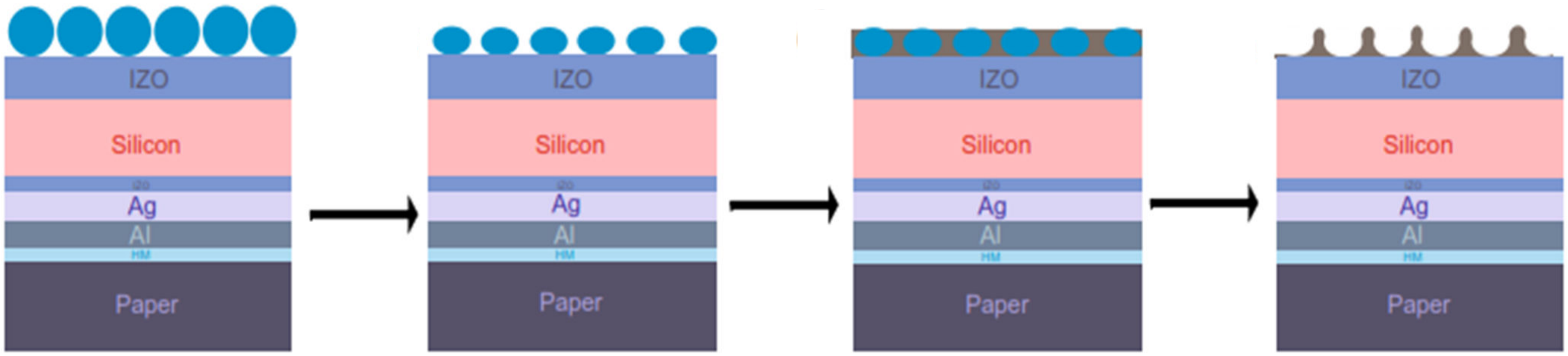


Maximum current enhancement with ideal Light Trapping

A. Bozzola et al. Optics *Express* **20** A224-A44 (2012)



Fabrication and next steps



- ✓ Fabrication of optimized TiO_2 mesostructures on glass
- ✓ Successful replication on IZO and Si
- ➢ *Next step*: device construction and testing