The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

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2234-25

Meeting of Modern Science and School Physics: College for School Teachers of Physics in ICTP

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Photovoltaics and sun energy

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Photovoltaics and sun energy

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CHOSE

EU Renewable Energy Road Map

The European Community has defined (10 Jan 2007) the following equation

20+20-20=2020

By 20**20** EU have to reduce by **20**% the CO_2 emissions increase by **20**% renewable energy and increase by **20**% the energy efficiency

http://ec.europa.eu/energy/index_it.html

Benefits:

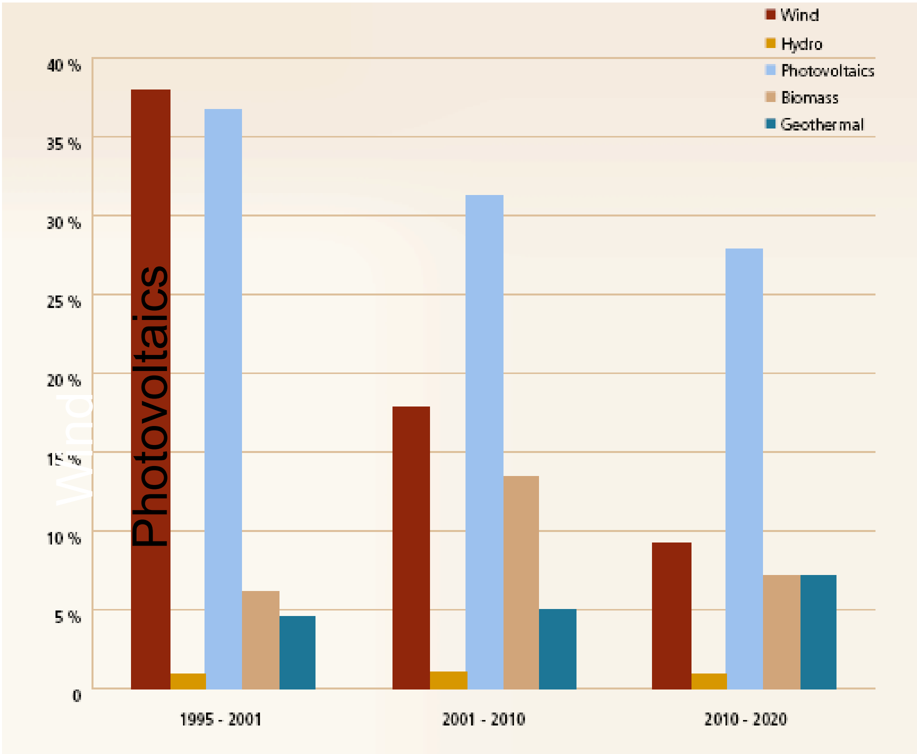
- 443 billion euro investment 2001-2020
- 115.8 billion euro gained from fuel reduction
- 130 - 320 billion euro gained from additional costs
- 2 milioni additional jobs

Renewable energy objectives (2020)

Electricity by renewable energies

Type of energy	1995 Eurostat	2001 Eurostat	AGR * 1995-2001	Projection 2010	AGR * 2001-2010	Projection 2020	AGR * 2010-2020
1. Wind	2.5 GW	17.2 GW	37.9 %	75 GW	17.8 %	180 GW	9.1 %
2. Hydro	87.1 GW	91.7 GW	0.9 %	100 GW	1.0 %	109 GW	0.9 %
3. Photovoltaics	0.04 GWp	0.26 GWp	36.6 %	3GWp	31.2 %	35 GWp	27.8 %
4. Biomass	6.1 GWe	8.7 GWe	6.1 %	27 GWe	13.4 %	54 GWe	7.1 %
5. Geothermal	0.5 GW	0.65 GW	4.5 %	1 GW	4.9 %	2 GW	7.1 %

Source EREC



Annual Growth Rate

Investment and jobs

Investment (billion euro)

	2001-2010	2011-2020	2001-2020
Wind	55	101	156
Photovoltaic	10	66	76
Biomass	44	45	89
Hydro	11	9	20
Geothermal	4	7	11
Solar Thermal	16	75	91
TOTAL RES	**140**	**303**	**443**

Jobs

	2010 jobs FTE	2020 Jobs FTE *
Wind	184,000	318,000
Photovoltaic	30,000	245,000
Biomass	338,000	528,000
Biofuels	424,000	614,000
Small Hydro	15,000	28,000
Geothermal	6,000	10,000
Solar Thermal	70,000	280,000
TOTAL RES	**1,067,000**	**2,023,000**

Source EREC

EU 2020 - PV technical objectives

Strategies of the
European Photovoltaic Industry Association (EPIA)

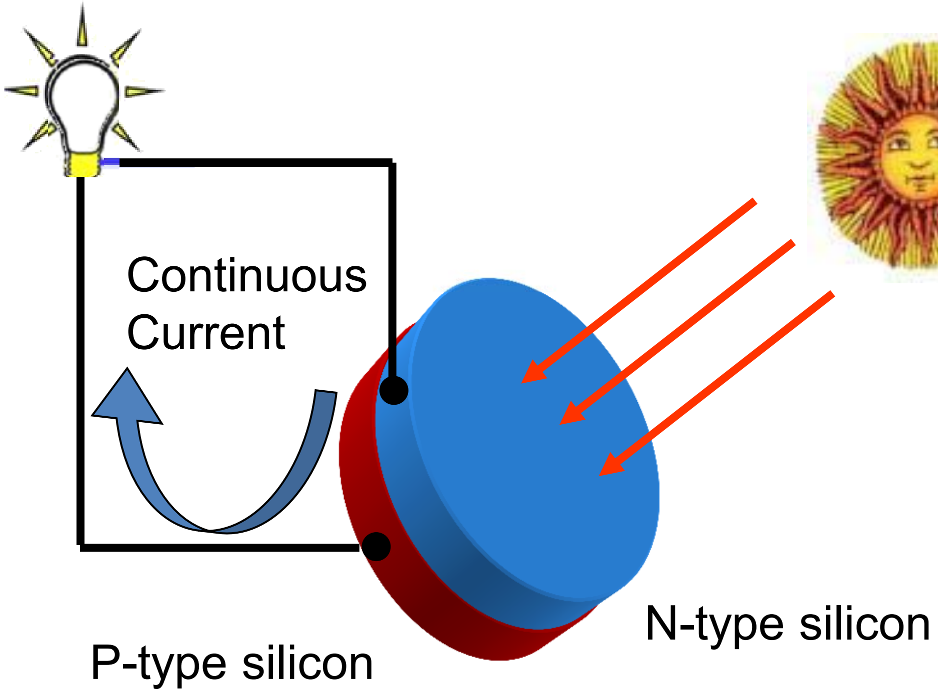
The European Photovoltaic Industry Association (EPIA) has defined a set of development strategies for achieving the goals of 2020.

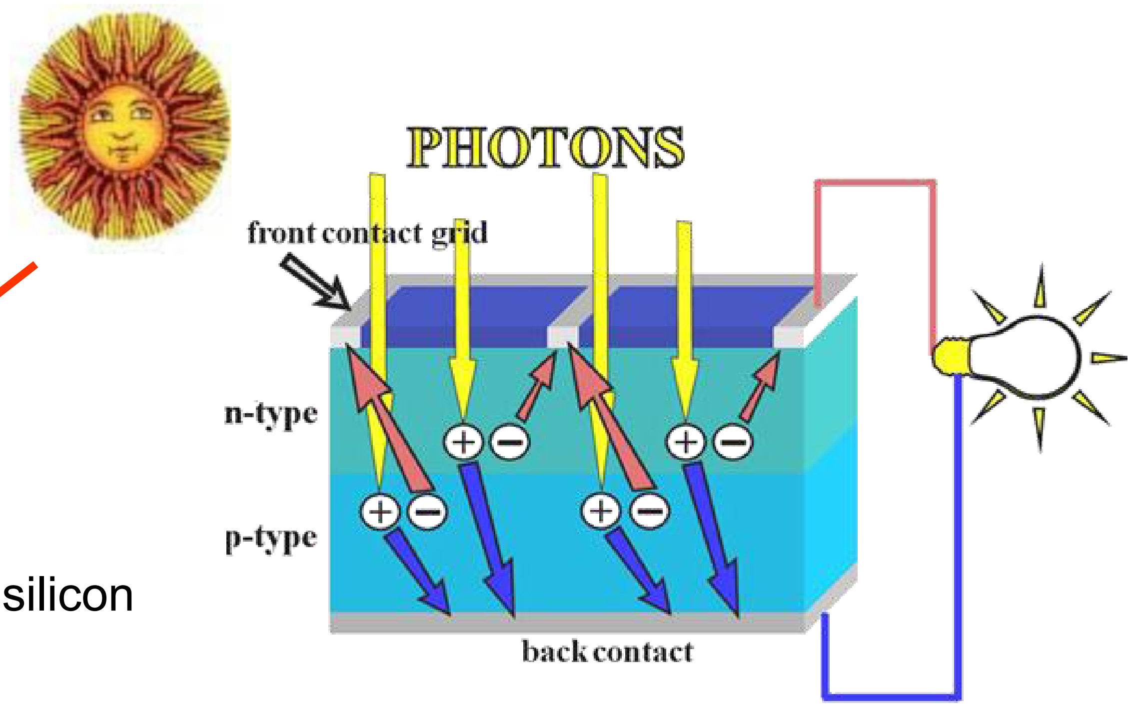
Besides increasing the efficiency of silicon modules, EPIA identifies the development of new materials and concepts as a crucial step for achieving these objectives.

Among these new concepts, particular emphasis has been given to organic cells and in particular to Dye Sensitized Solar Cells (DSC).

EPIA considers the DSC as the most mature amongst the OPV technologies and thus pushes for a decisive plan for its research and development that can deliver the first production lines in the near future.

Photovoltaic cell: working principle





"Conventional" photovoltaic cells are based p-n junction between semiconductors.

Photovoltaic cell: short history

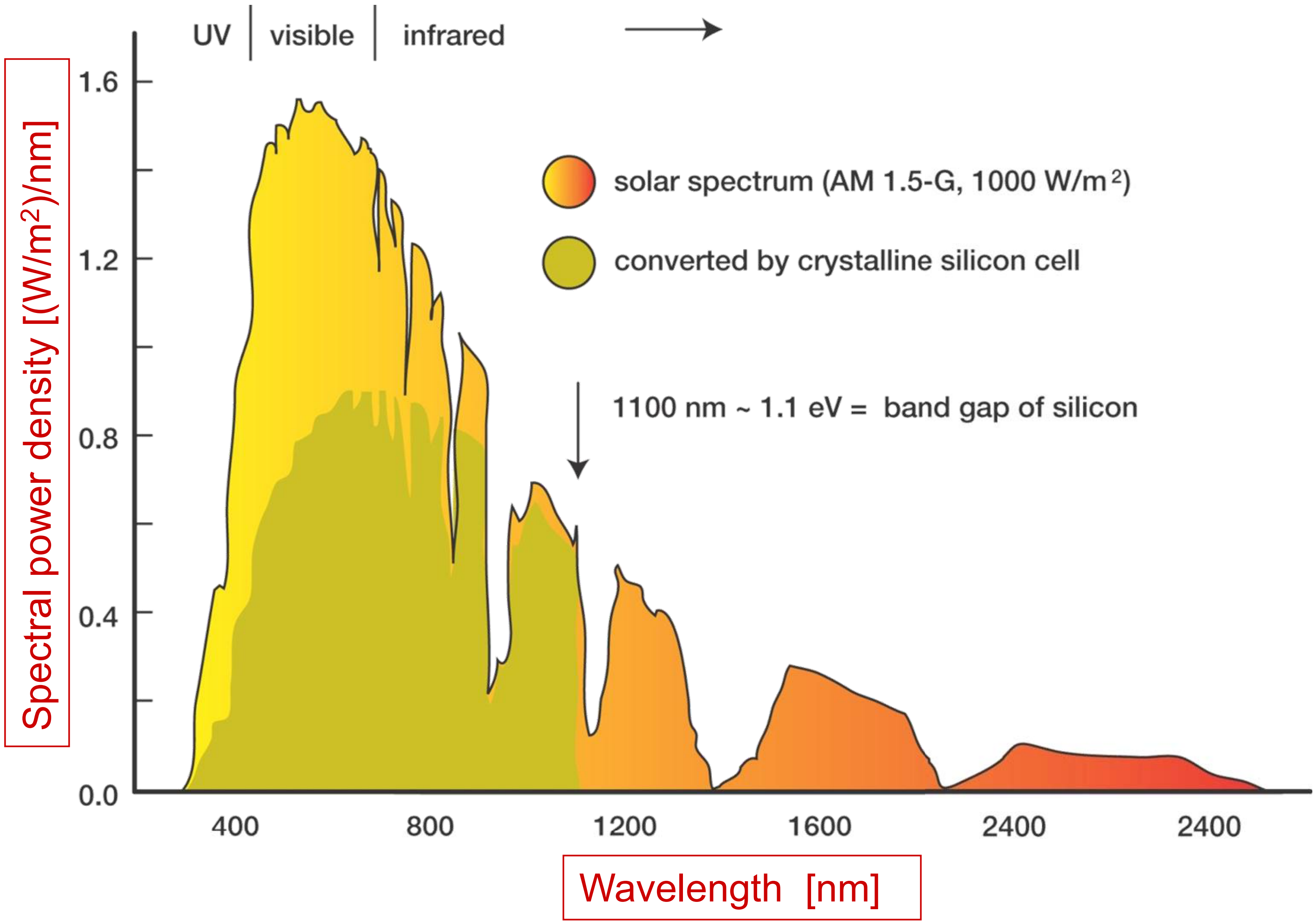
1941

Russell Ohl (Bell Labs) discover the silicon p-n junction and the effect of light on the junction

1954

Bell Labs researchers Pearson, Chapin, e Fuller demonstrated the photovoltaic cell with 4.5% efficiency

Solar Spectrum

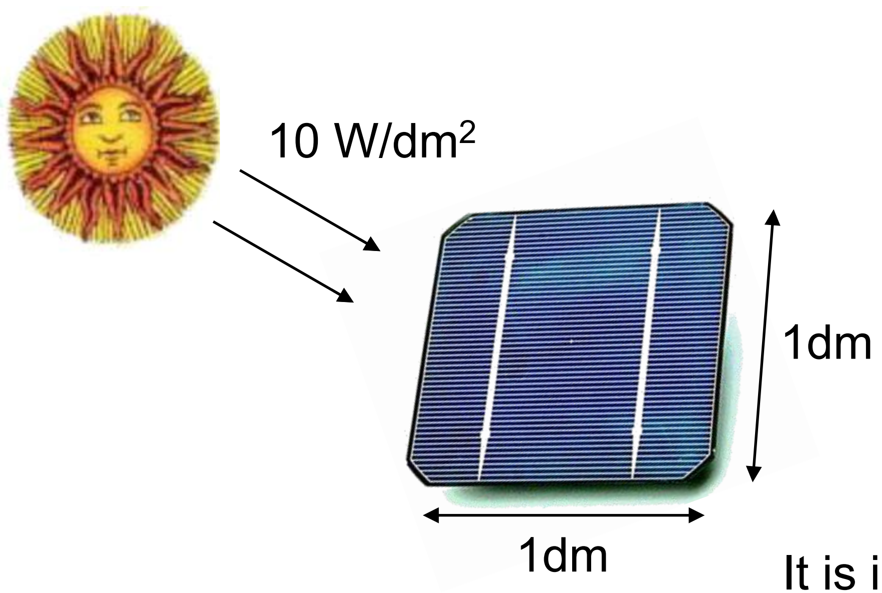


Efficiency

One of the most important parameters of the photovoltaic cell is the efficiency defined as:

$$\text{EFFICIENCY} = \eta = \frac{\text{Max electrical power produced by the cell}}{\text{Total solar power impinging on the cell}}$$

Example:



η = 10% → 1 W

η = 20% → 2 W

It is important to increase as much as possbile the efficiency.

Which are the factors influencing the cell efficiency ?

EFFICIENCY

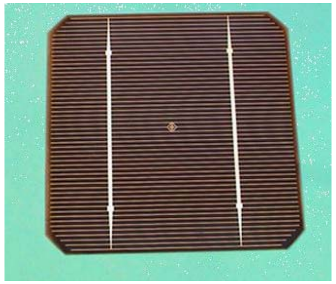
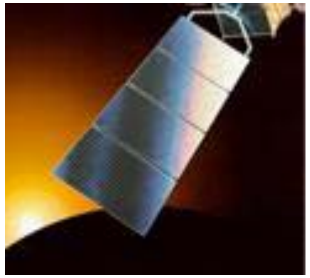
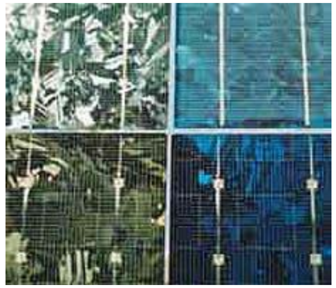
MATERIALS

Silicon
GaAs
CdTe
…..
…..

TECHNOLOGY

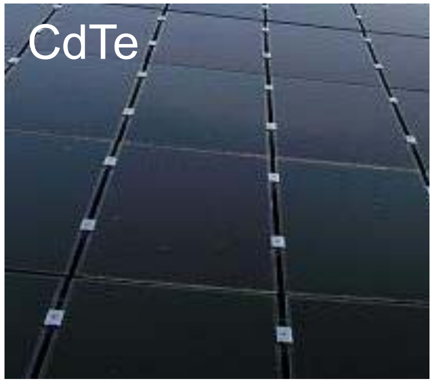
Single junctions
Multiple junctions
….
….

Materials for photovoltaic cells

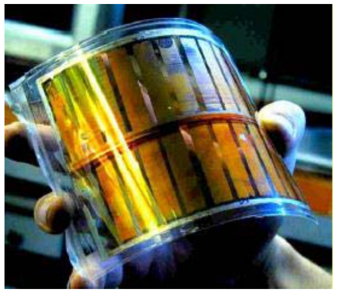

Bulk semiconductors

- **Silicon**
  - Single crystal
  - Multi crystalline
- **Gallium arsemide (GaAs)**
- **Other III-V semiconductors**



Thin Films semiconductors

- Amorphous silicon (a-Si)
- Cadmium telluride (CdTe)
- Copper-Indium diselenide (CuInSe2, o CIS)
- Coper-Gallium-Indium diselenide (CIGS)



Organic and hybrid materials

- Small molecules
- Polymers
- Dye Sensitized Solal Cell

Beyond the Shockley-Queisser limit

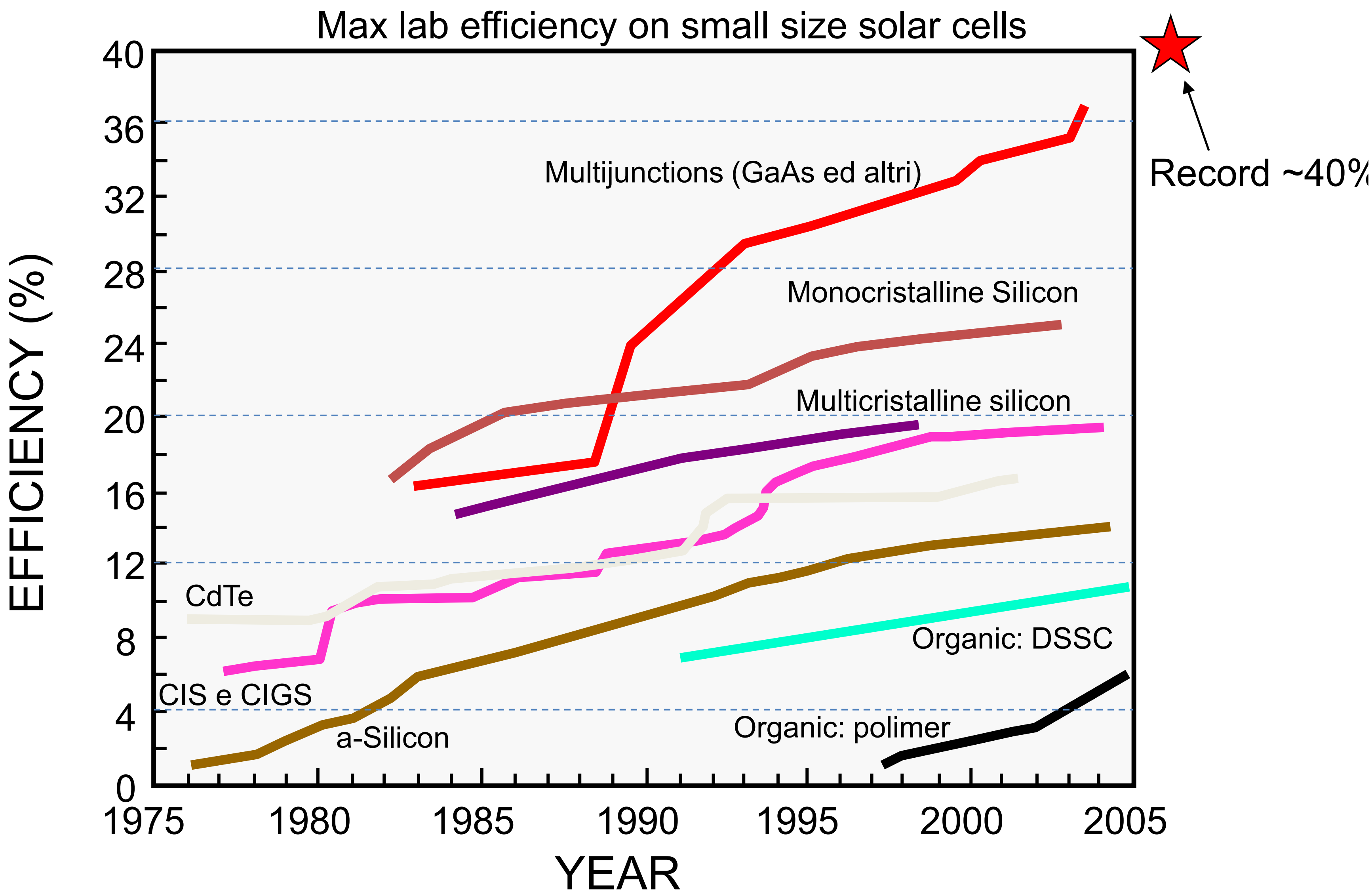
The maximum thermodynamic efficiency for the conversion of unconcentrated solar irradiance into electrical free energy in the radiative limit, assuming detailed balance, a single threshold absorber, and thermal equilibrium between electrons and phonons, was calculated by Shockley and Queisser in 1961to be about 31%.

W. Shockley and H. J. Queisser. *J. Appl. Phys.* 32 (1961) 510.

What do we do to achieve efficiencies > 31 % ?

- Concentration
- Multijunction
- No thermal equilibrium

Lab Cell efficiency

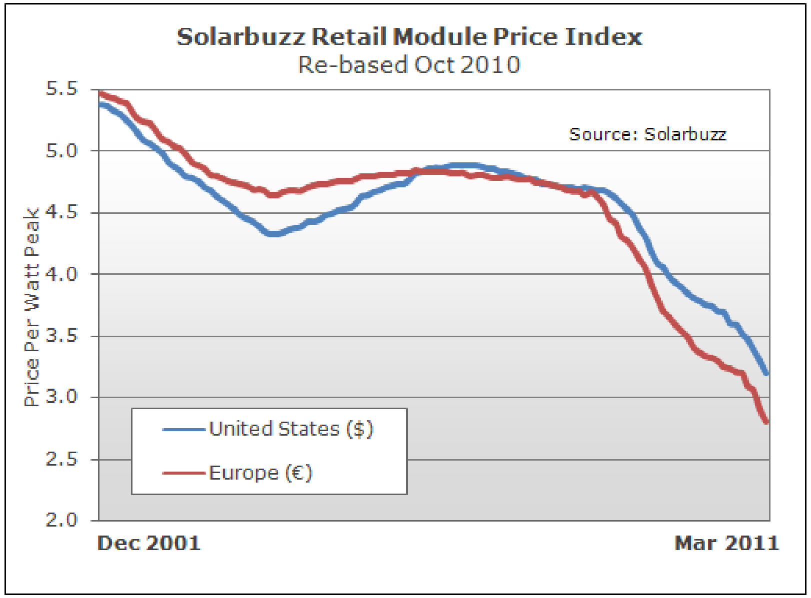


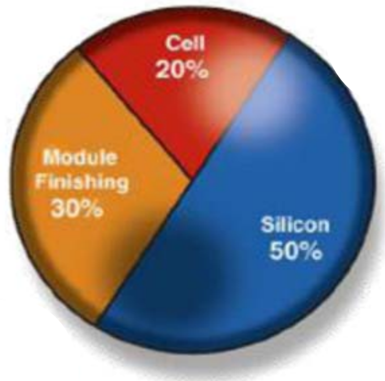
Energy from the sun

To satisfy the electricity needs of a typical family one needs 3kWp PV system, i.e. ~20m^2 of photovoltaic surface (assuming system efficiencies of 15%).

COST → 12.000 euro

Cost reduction of PV systems per Wp/m^2 becomes paramount in order to make PV technology an important instrument for energy production.





Could we reduce cell costs ?

Cost of silicon wafers is high (2 euro/ Wp, one doping level)

Production equipments are expensive

- **100 Meuro for 40 MWp/year amorphous silicon**
- **15 Meuro for 30 MWp/year bulk silicon**

Is it possible to produce photovoltaic cells by reducting production and material costs ?

Moreover, is it possible to create a photovoltiac module suited for Building Integration (control on colour, transparency etc) ?

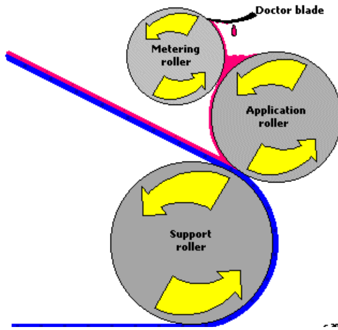
This is possible but we have to re-invent the cells and the fabrication processes

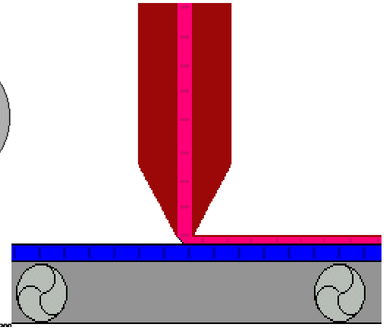
Organic photovoltaics

“New” manufacture processes

Conventional Electronics → **Organic Electronics**

Conventional semiconductor industry → **Printing methods**





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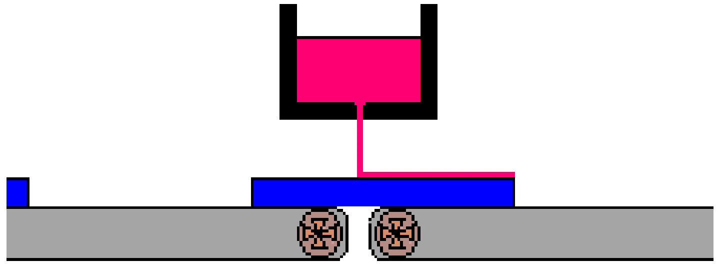
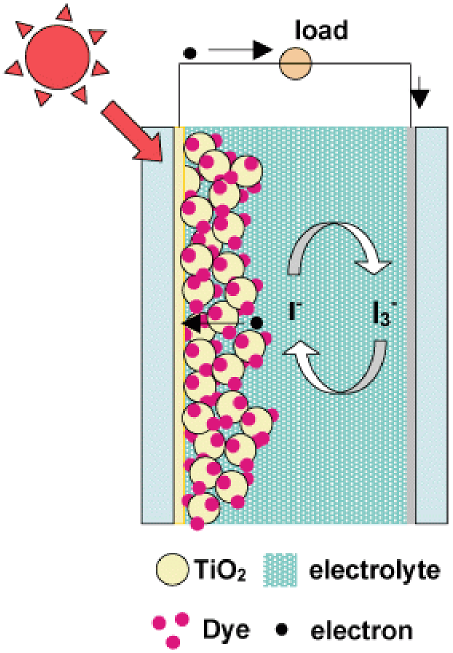


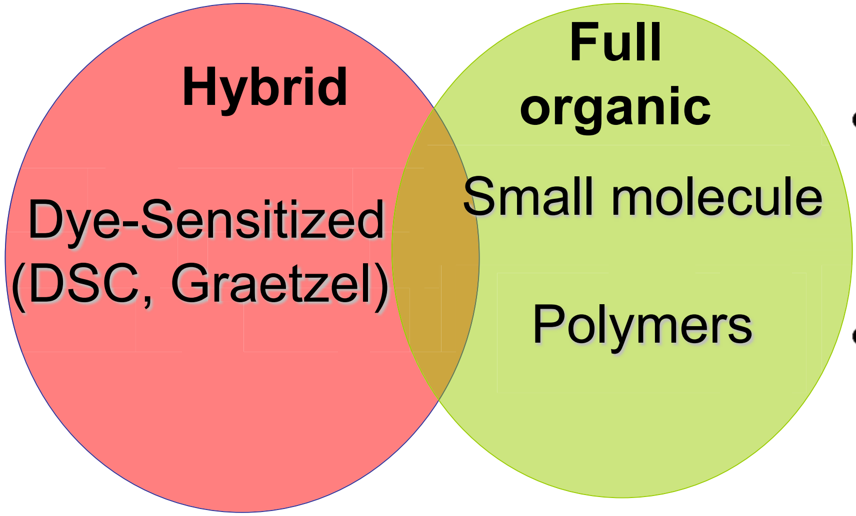
High temperature, doping, vacuum

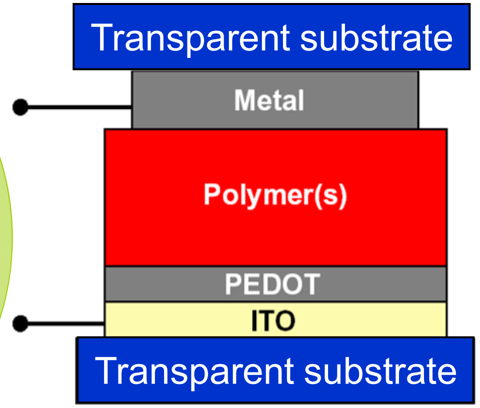
Liquid deposition

Very Large enterprises → **Small Medium enterprises / local productions**

Organic photovoltaics

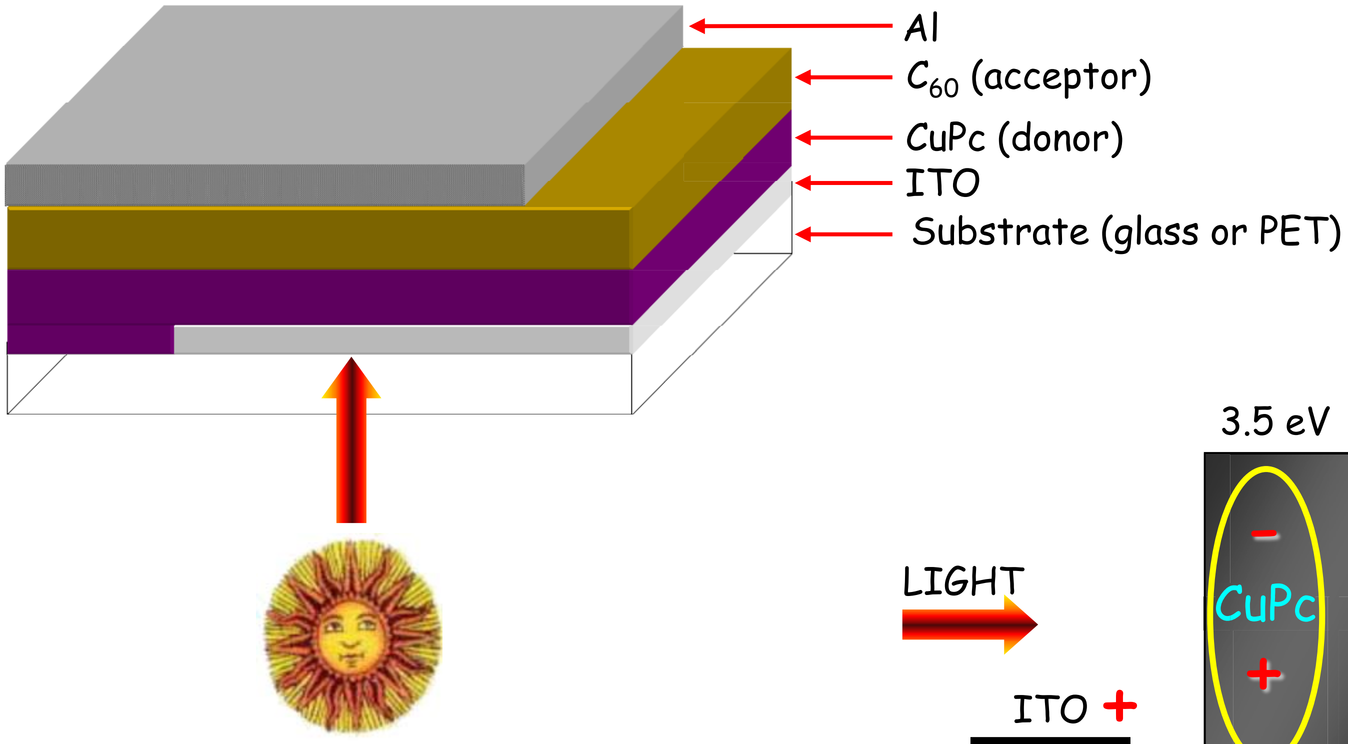


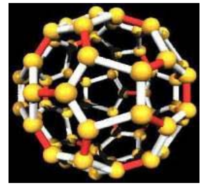


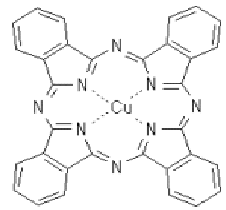


Type	**Max lab efficiency**	**Stability**	**R&D**
Hybrid Dye Sensitized (Graetzel)	~ 11-12%	20 years	University and industry
Full organic solar cells	~ 8%	3 years	University and industry

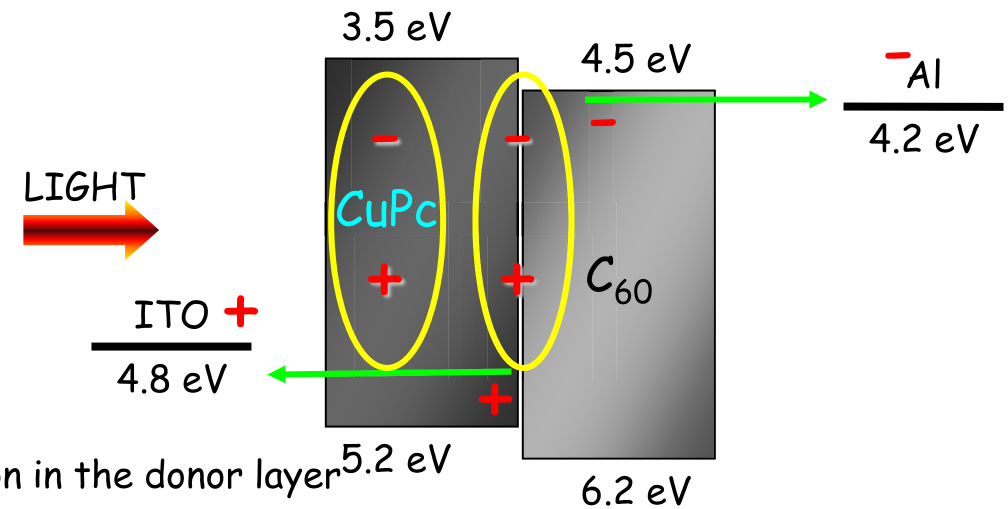
Small Molecules Organic Solar Cell







How it works



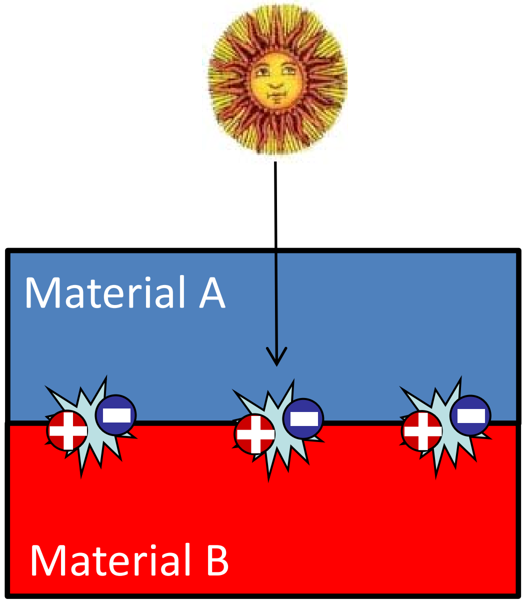
1) Creation of an exciton via absorption of a photon in the donor layer
2) Diffusion of the exciton to the interface with the acceptor.
3) Dissociation of the exciton in a e^- and a *h+* at the interface (charge transfer).
4) Transport of the free charges to the opposite electrodes (electrons towards Al and holes towards ITO).

Charge separation at the 2D interface between donor and acceptor

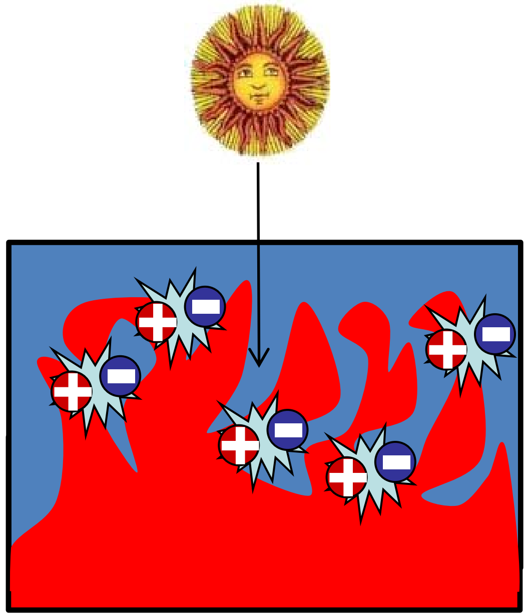
Breakthrough concept: bulk heterojunction

Heeger - Friend

Classical Heterojunction



Bulk Heterojunction



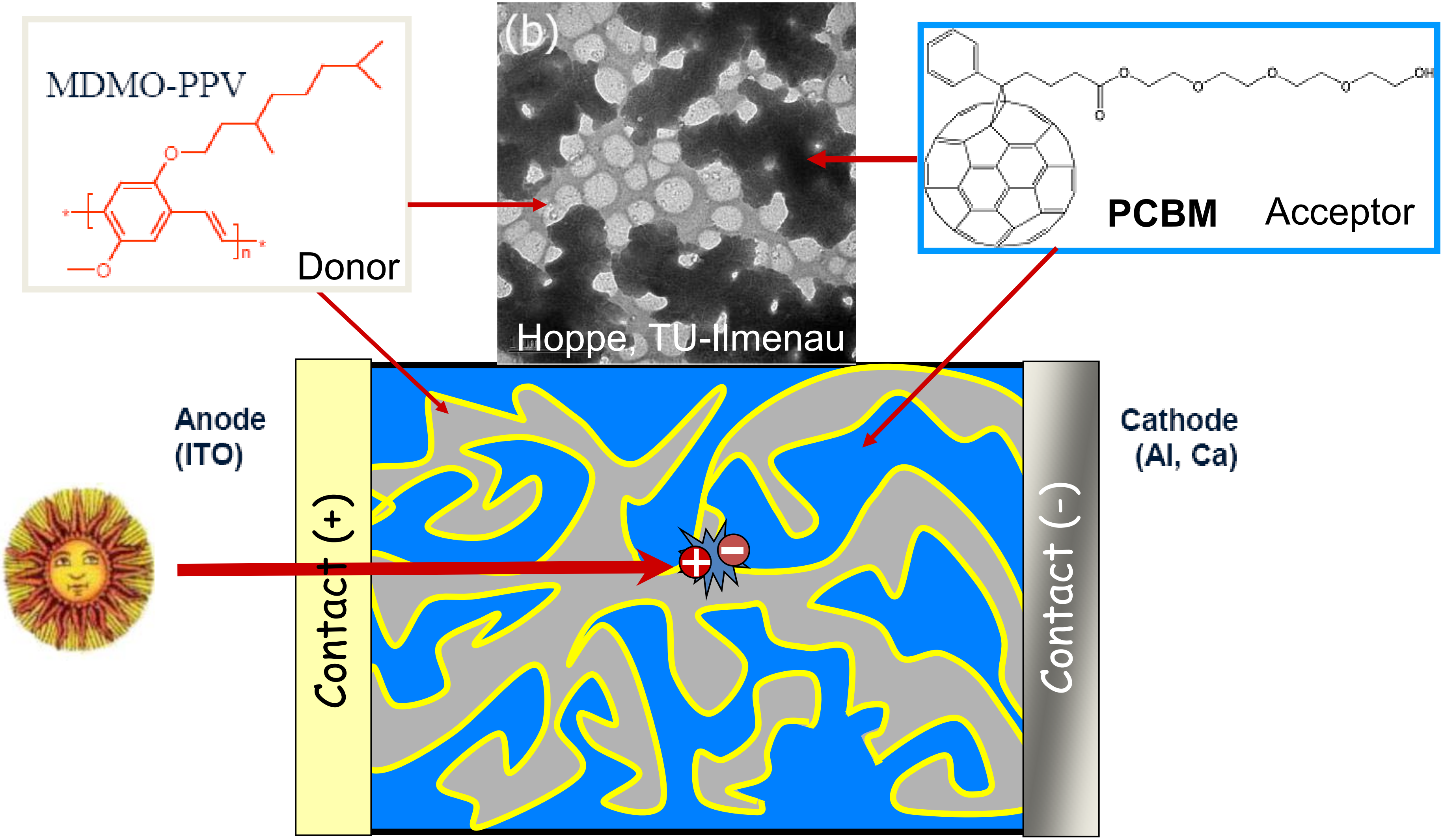
Interface between A and B materials is two dimensional (2D)

After abosption of ligth, e-h dissociate at the interface

Interface between A and B material tends to be three dimensional (3D) !!!

Absorption surface and dissociation interface increase. More efficient

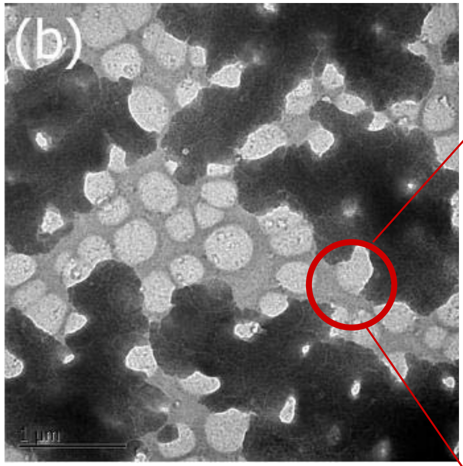
Polymer Solar Cells (Bulk heterojunction)

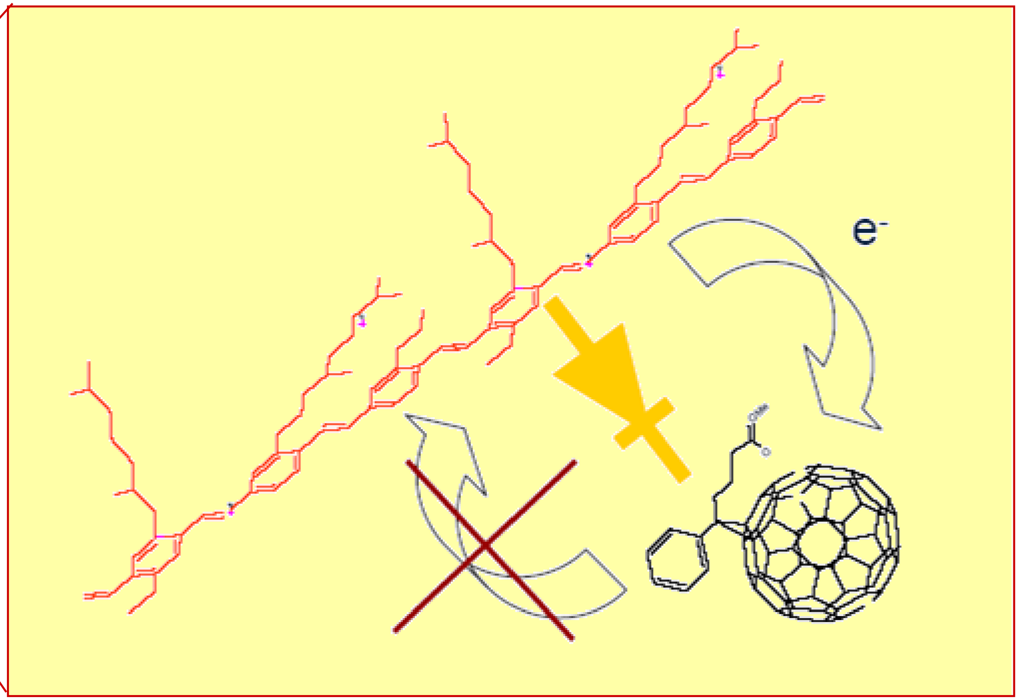


Intimate mixure of electron donor and acceptor materials

Charge separation at the distributed interface + percolation to the contacts

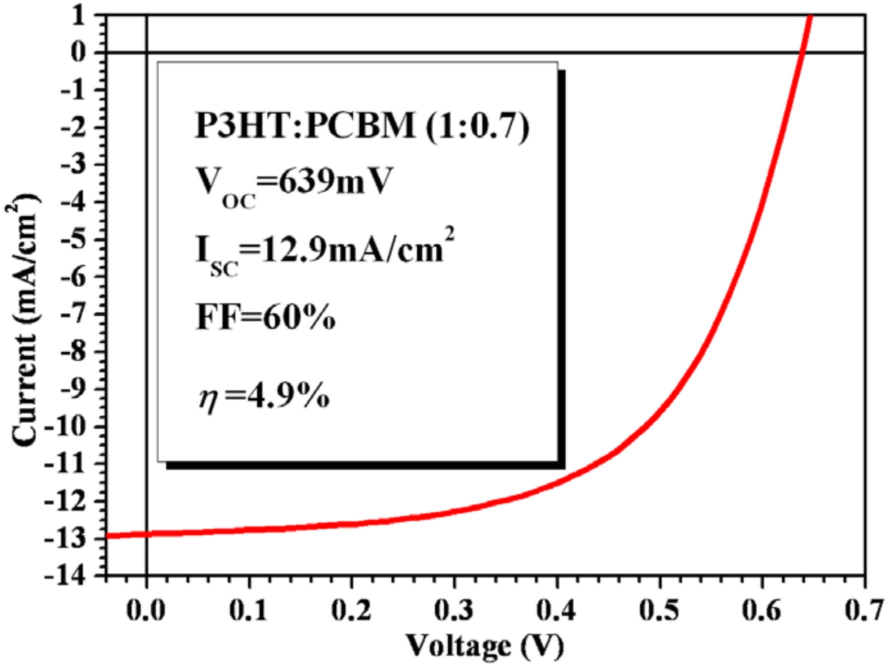
Bulk heterojuction=distributed molecular diode



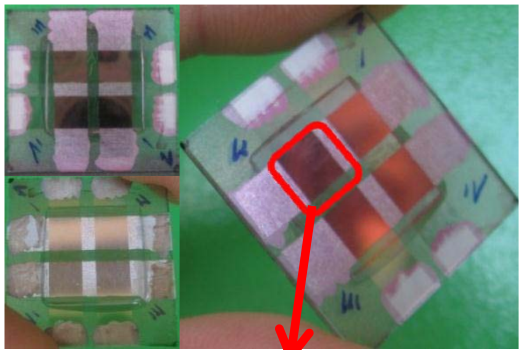


- Any PV device must have a rectifying interface which separates charges (== current/voltage asymetry == diode).
- A “bulk heterojunction” is the homogenous distribution of molecular diodes (hetero interfaces) within a semiconductor bulk.

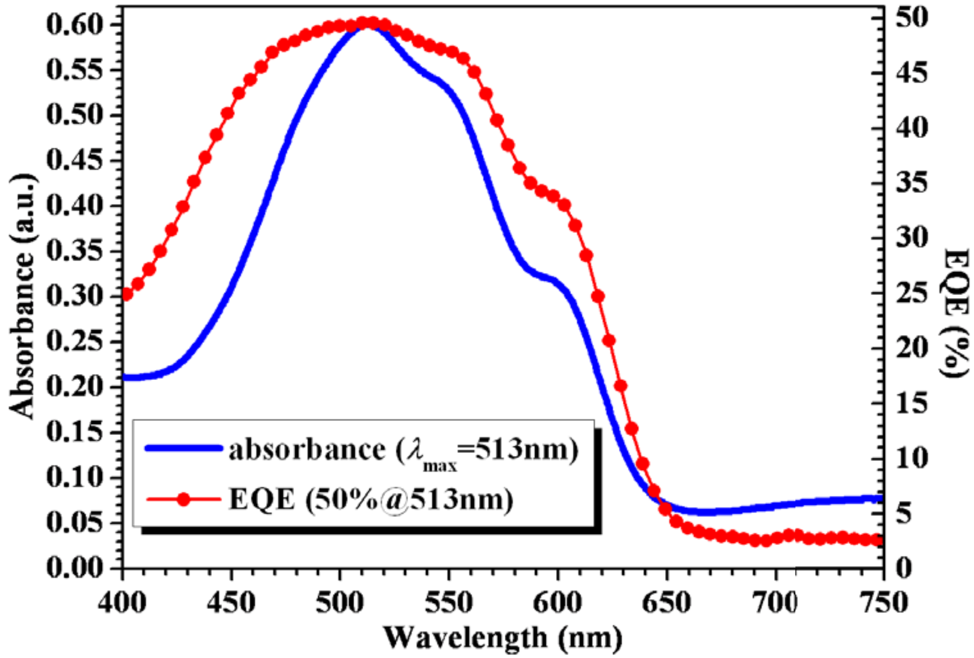
Organic Solar Cell (OSC)



Best realized device (η~5%)
Pedot:PSS (2000rpm → drying at 150°Cx10min)
P3HT:PCBM (400rpm → drying at RTx2h)
Thermal annealing (150°Cx10min after Al)

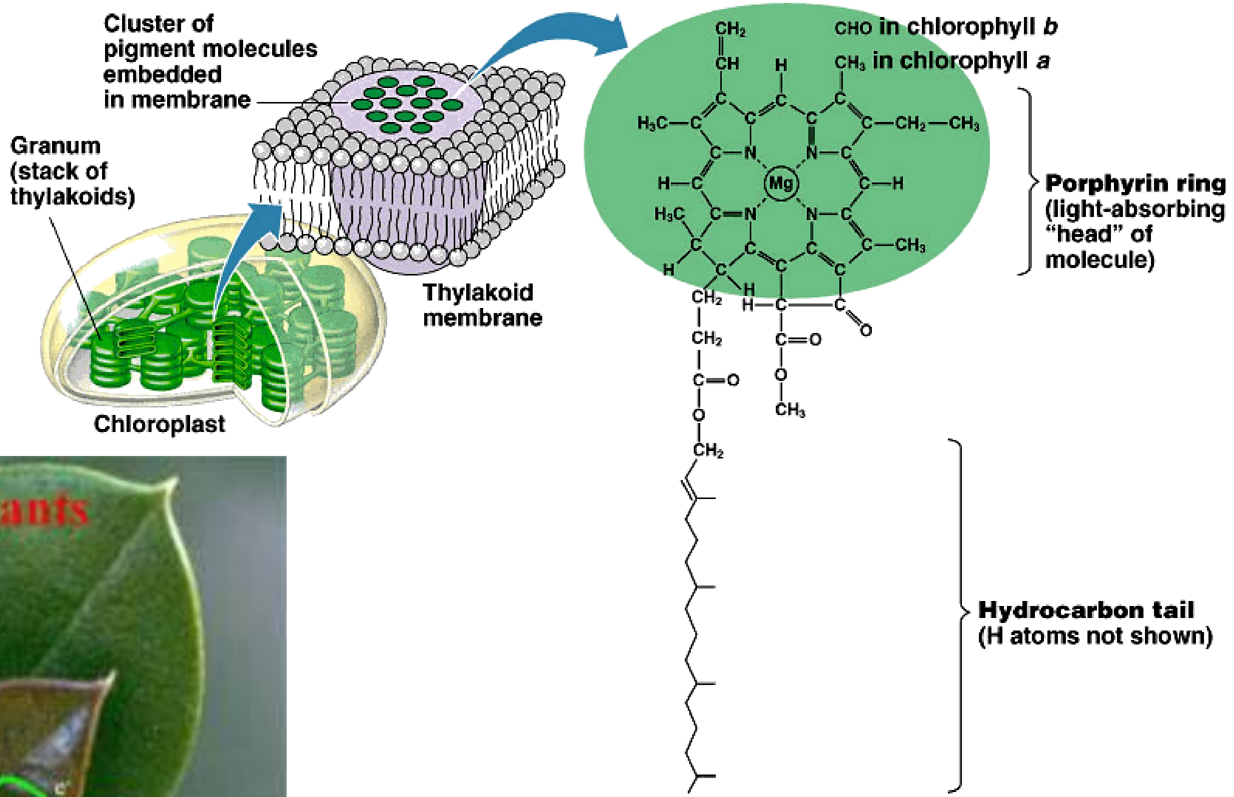


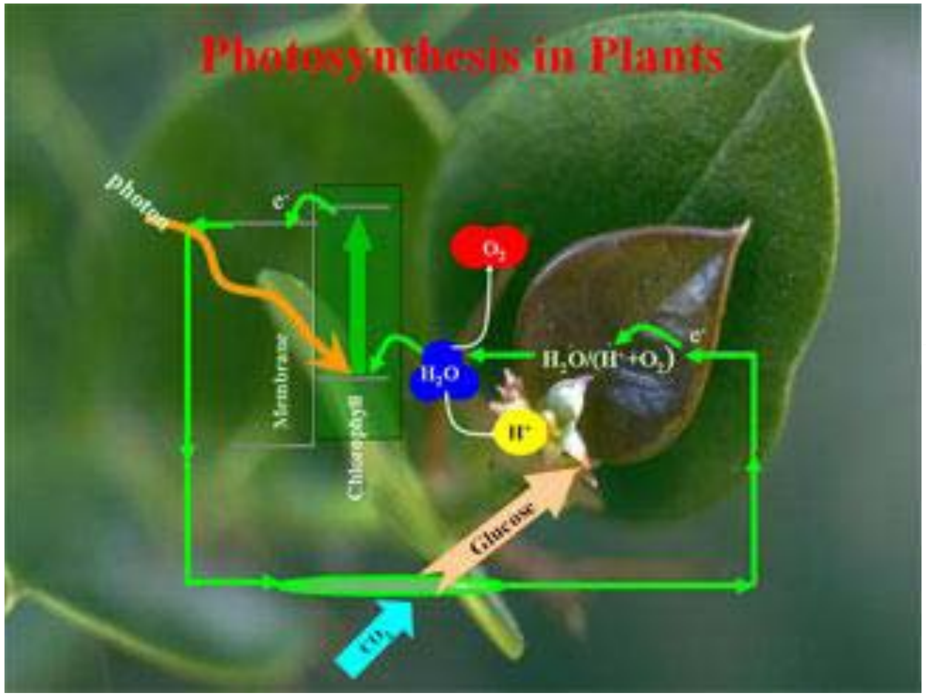
Area≈5x5mm^2



Bio-Inspired Solar Cell

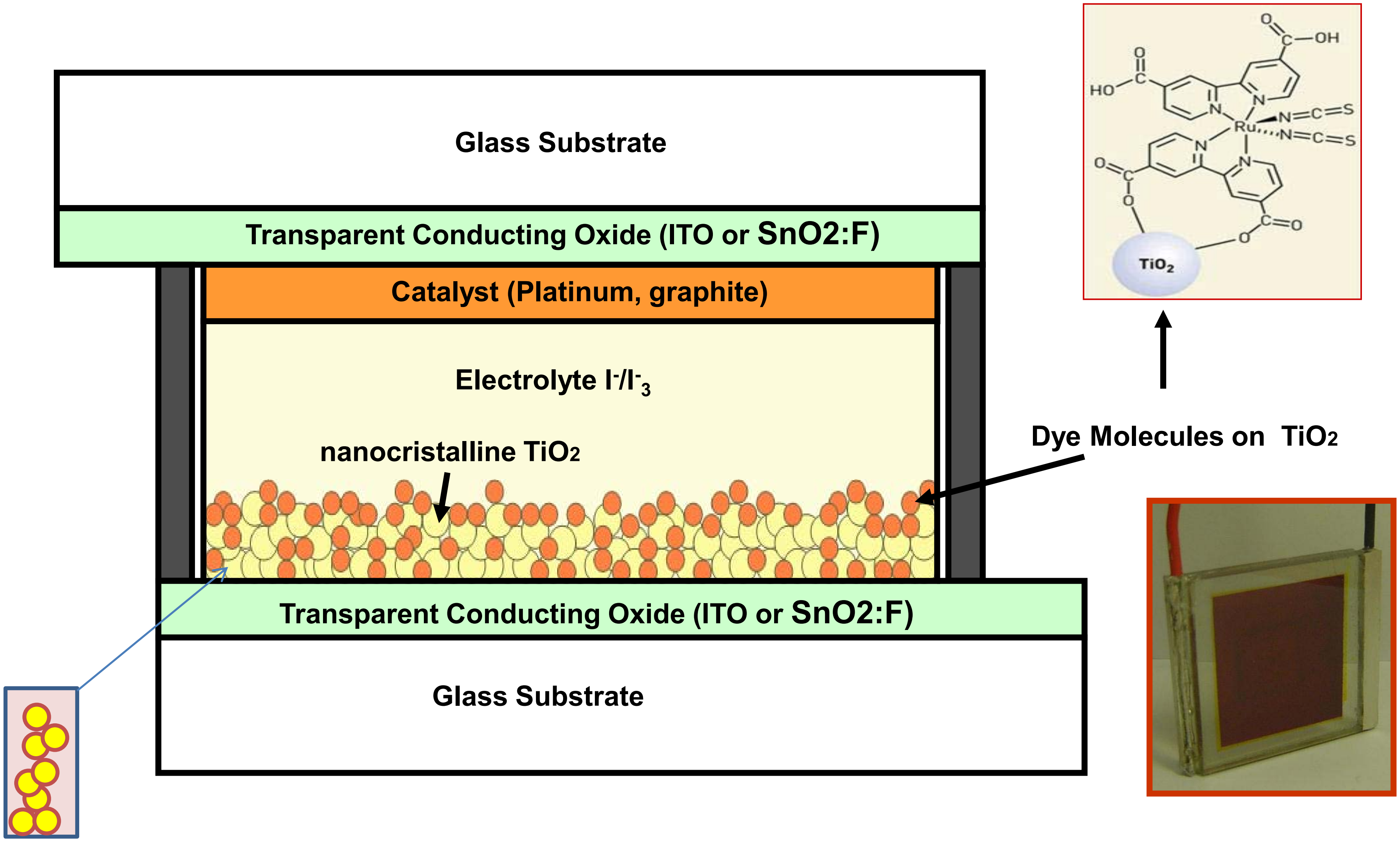
From Photosynthesis to …



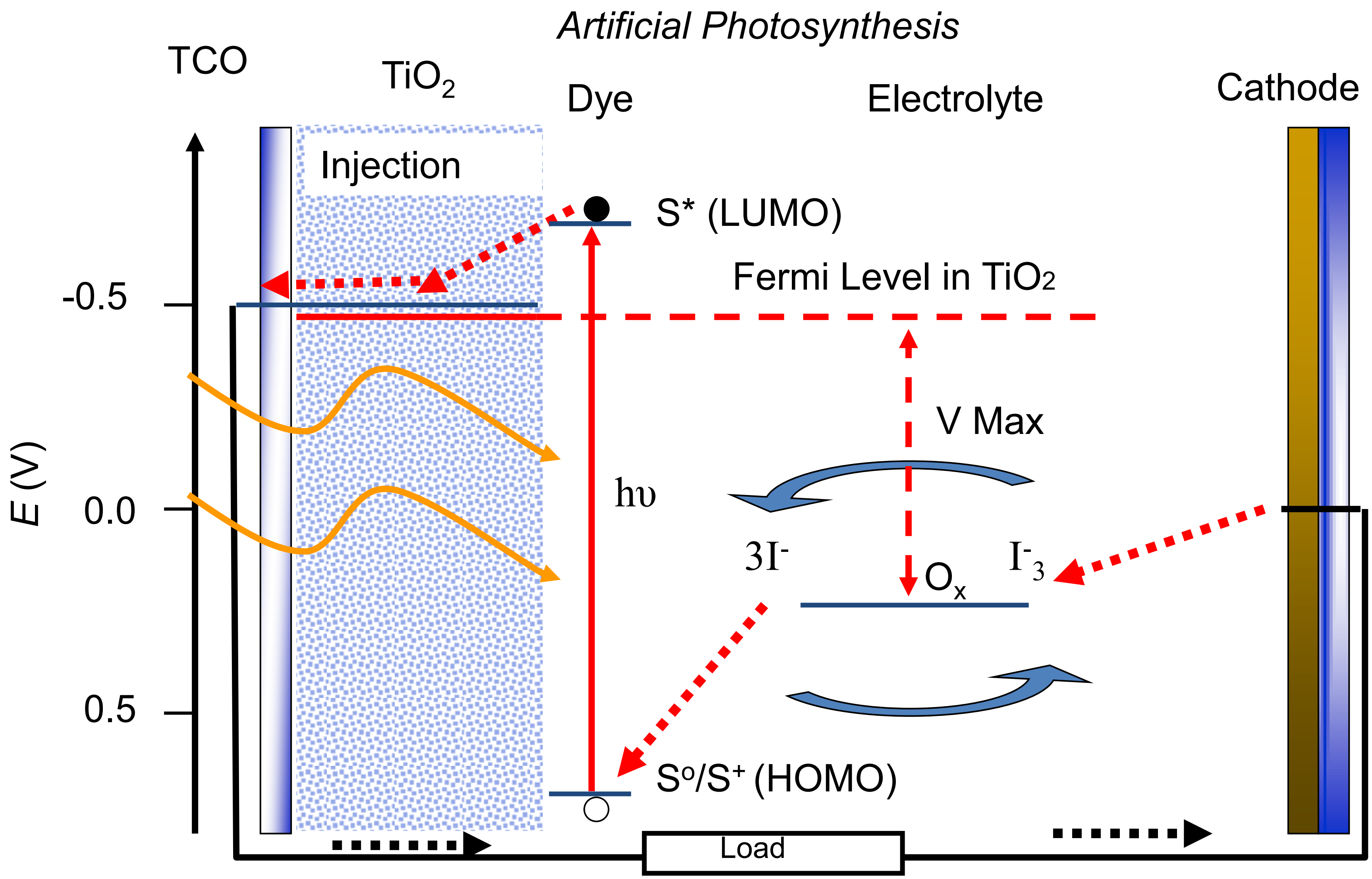


… Dye Sensitized Solar Cells

Dye Sensitized Solar Cells

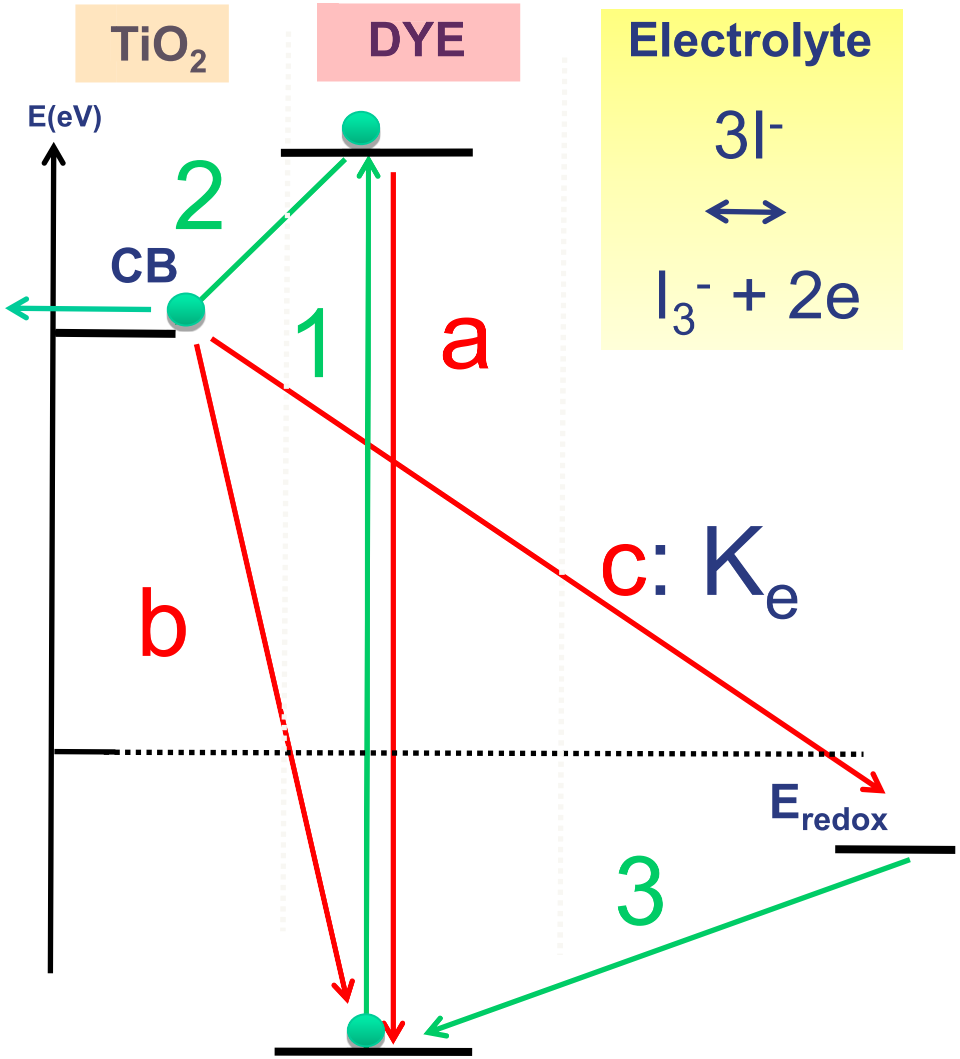


Working principle of DSC



No permanent chemical transformation in the materials composing the cell

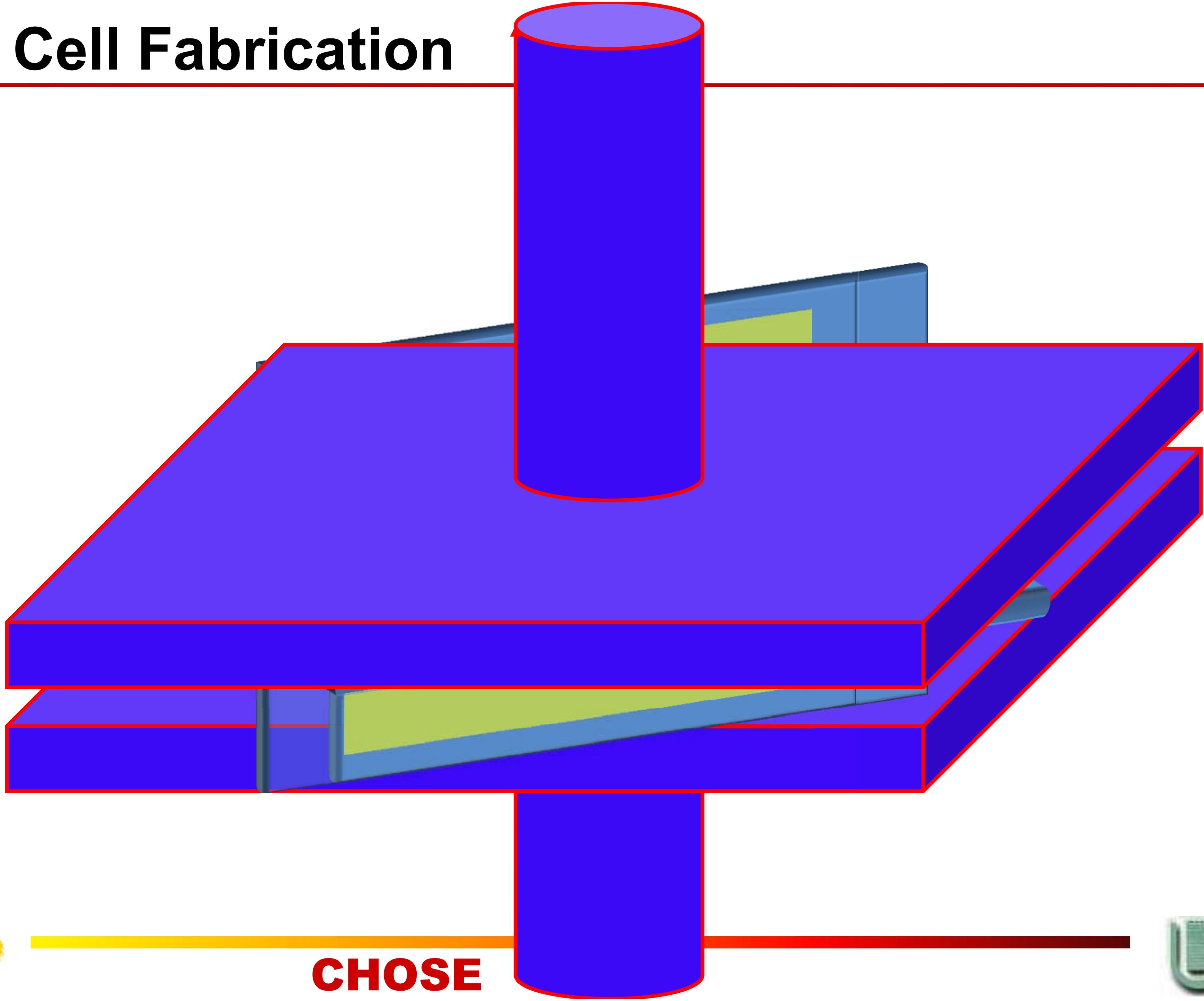
DSC Kinetics



1. Dye Excitation
2. Electron Injection into TiO$_2$ Conduction Band
3. Oxidation of the electrolyte

a. Dye relaxes into its ground state
b. Dye regenerated by TiO$_2$
c. Electrolyte Reduces at TiO$_2$ surface

Cell Fabrication



Automatic Screen-Printing (Baccini)

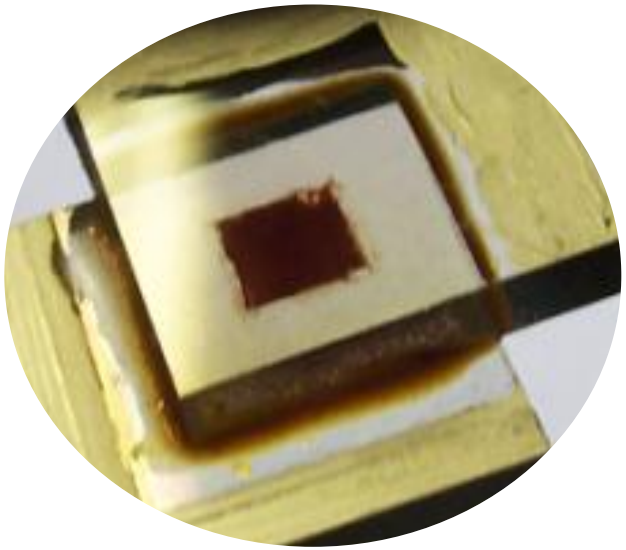
Cell optimization

Optimization parameters

(an engineer view)

TiO_2

Dye



Electrolyte

Couter-Electrode

Encapsulation

Layout

Printing Technique

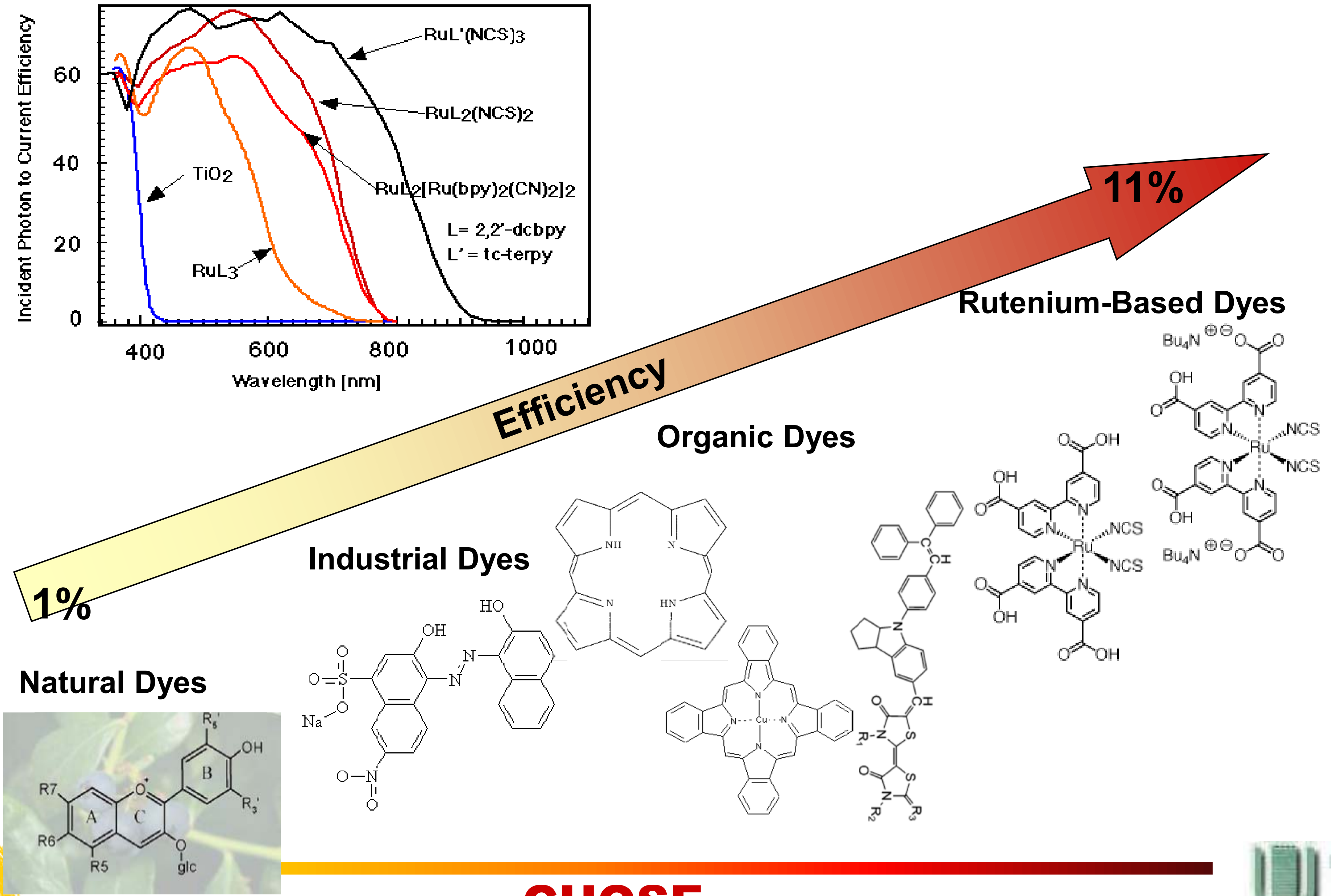
Easy

Mediu
m

Critical

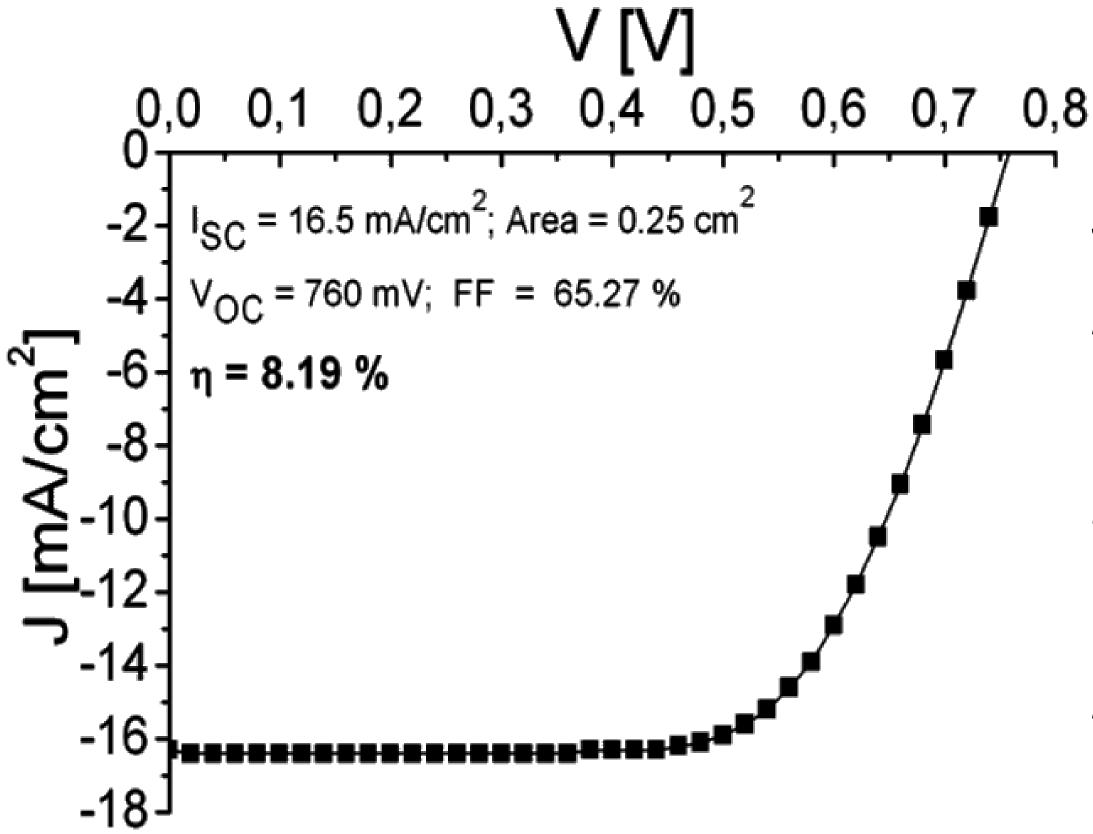
Difficult

Dyes



Incident Photon to Current Efficiency
60
40
20
0
400
600
800
1000
Wavelength [nm]
RuL'(NCS)3
RuL2(NCS)2
RuL2[Ru(bpy)2(CN)2]2
TiO2
RuL3
L= 2,2'-dcbpy
L' = tc-terpy
Efficiency
1%
11%
Natural Dyes
Industrial Dyes
Organic Dyes
Rutenium-Based Dyes

Comercial TiO_2: Standard Characteristics



Fabrication Process:

✓ *TiO_2 Dyesol Paste 18-NRT*

sintered 525°C @ 30’

final thickness 17.5-18.5 μm

✓ *Dye N719 Solaronix*

time dipping 15h

✓ *CE Platisol Solaronix*

fired 400°C @ 5’

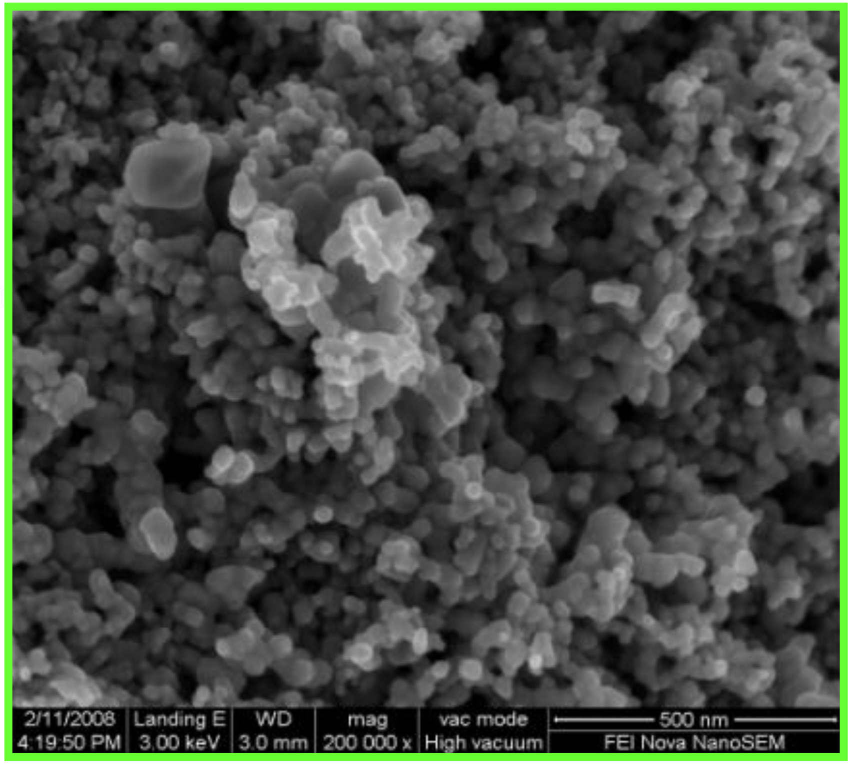
✓ *Spacer Surlyn 60 μm*

✓ *Electrolyte Dyesol HPE*

Process Improvements 1/2

Introduction of $TiCl_4$ treatments

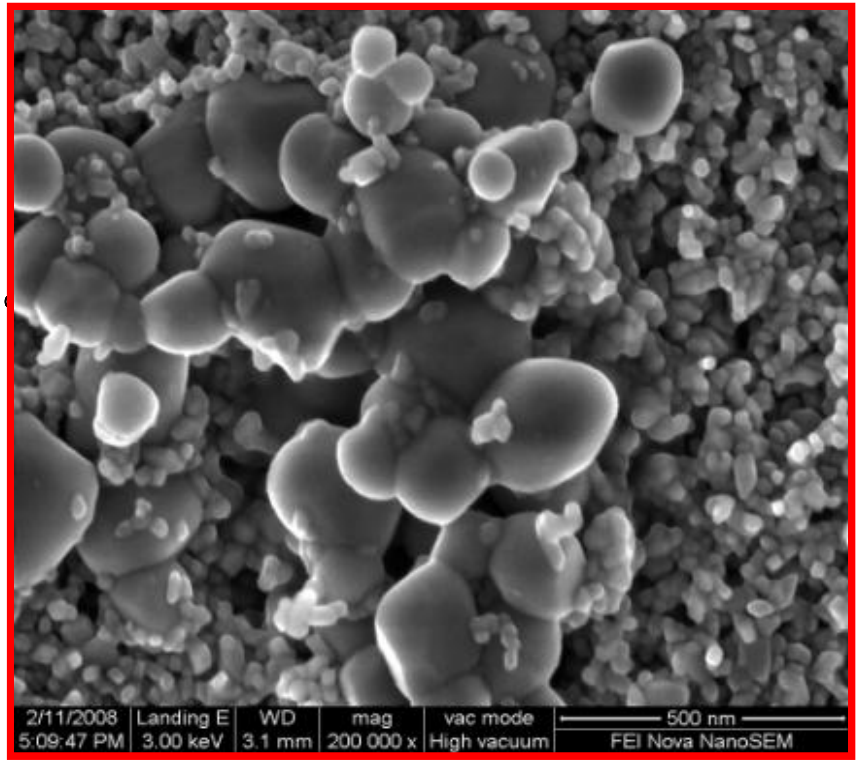
Pre TiO_2 deposition + post sintering treatments
$TiCl_4$ solution 40mM 30' @ 70°C



Transparent

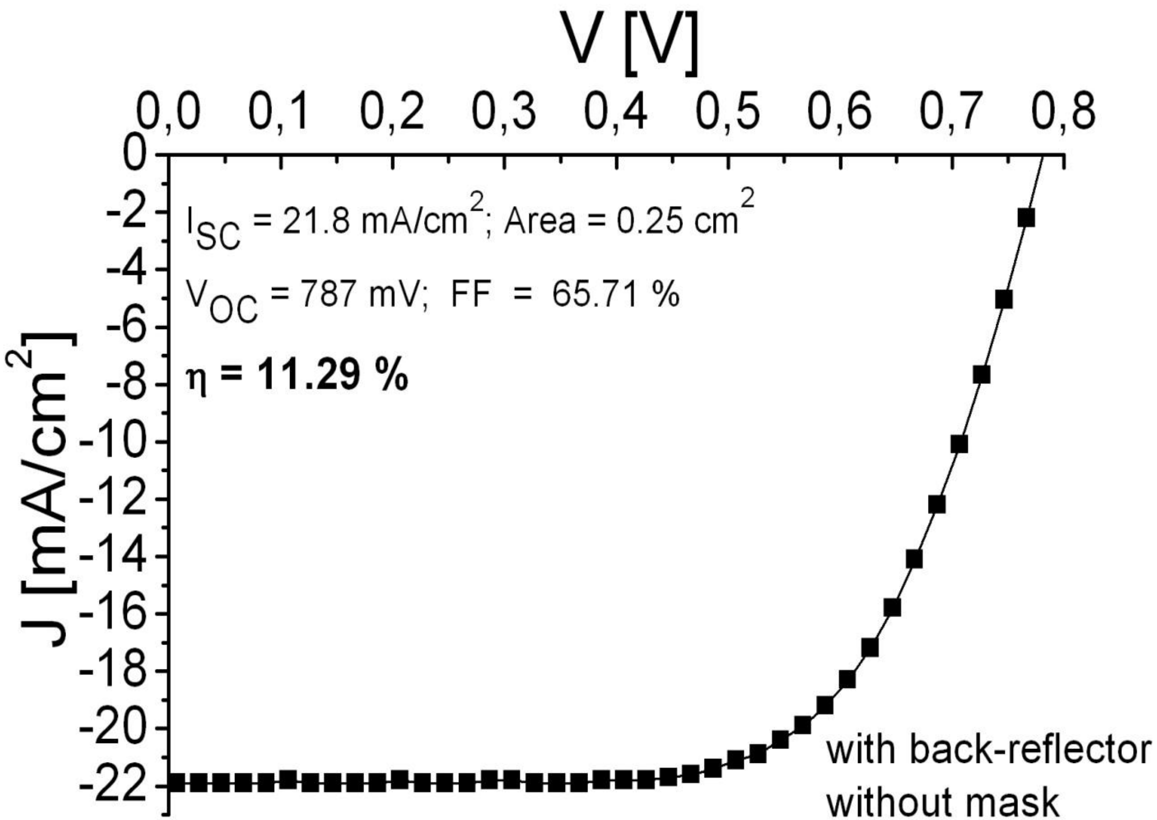
Introduction of scattering layer

TiO_2 Dyesol scattering paste WER4-0
Thickness 8 μm*



Not Transparent

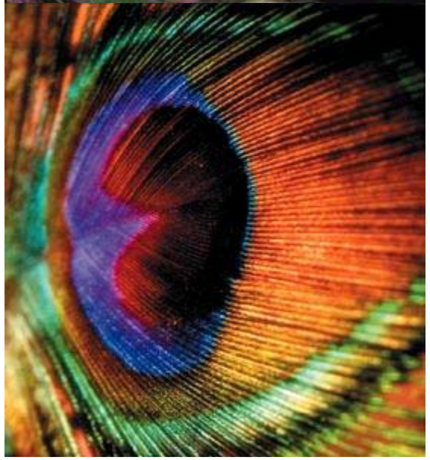
Process Improvements 2/2



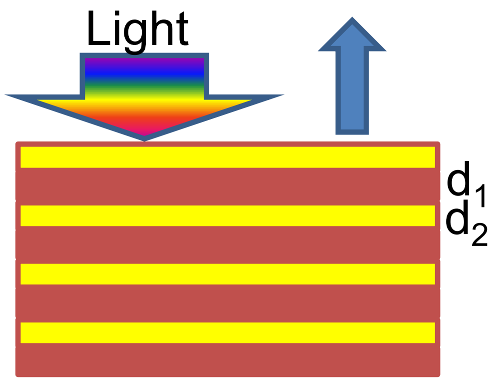
I/V Characteristics of the $TiCl_4$ treated cell measured with the introduction of back-reflector

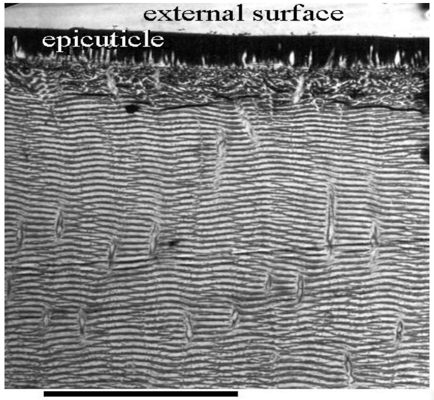
Good reproducibility within 2% deviation

Artificial colors with Photonic Crystals



Photonic Crystals are periodic structures, there are natural examples already existing in nature, for instance, the microstructure in the wings of some butterflies causes their remarkable iridescent colours. This structures reflect electromagnetic radiation as propagation through them is prohibited. The action of electromagnetic repulsion / reflection, whatever the frequency at which it occurs, is due to the fabric of the crystal. The periodicity of the crystal plays a very important role in the formation of a useful band gap. The actual width of this band gap depends on the geometry, feature size, spacing and the materials which make up the crystal. The manipulation of light with artificially manufactured photonic crystals is an important new research area.

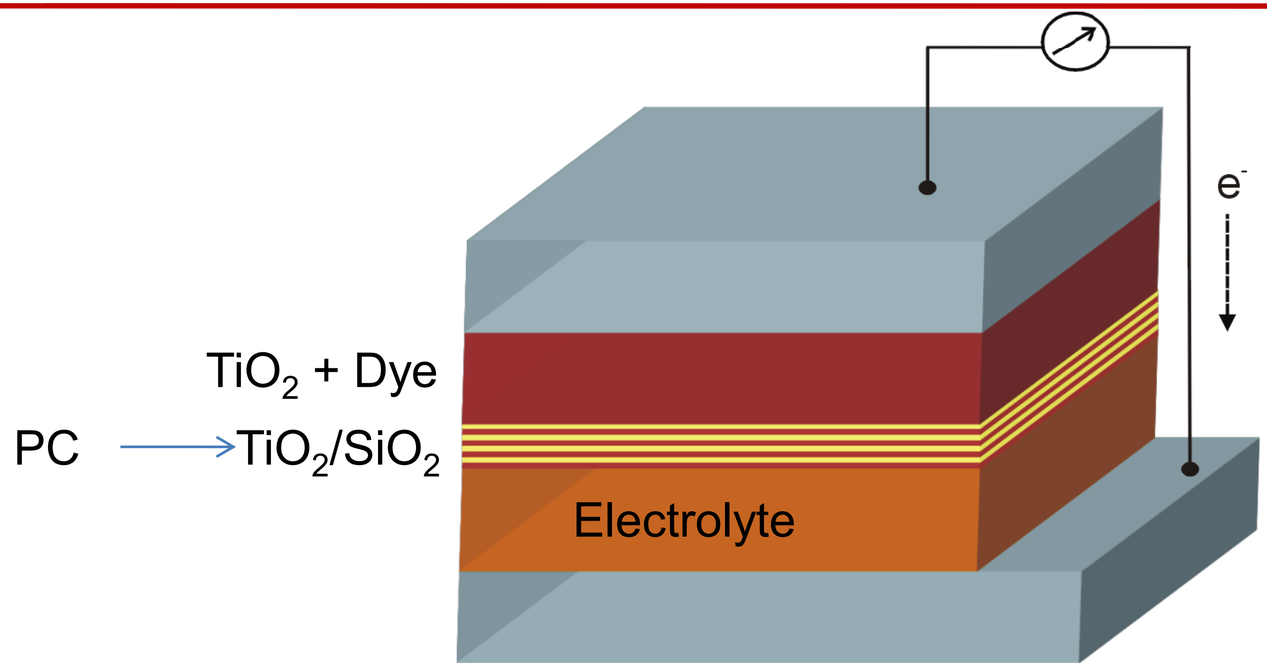




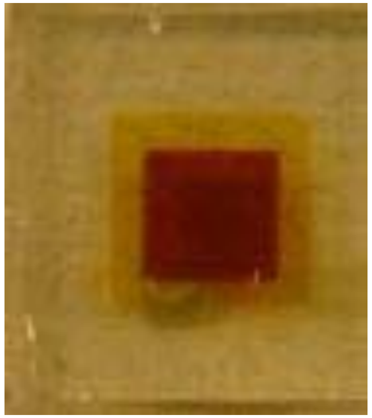
1D Photonic Crystal

$$\lambda_{BRAGG} = 2(n_1 d_1 + n_2 d_2)$$

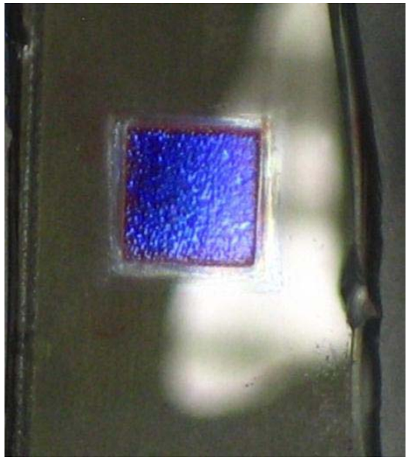
Dye Solar Cells with Photonic Crystals (PCs)



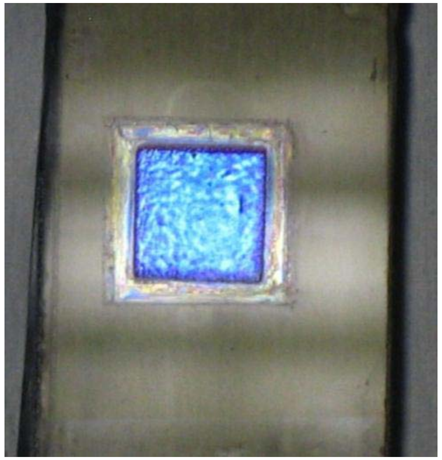
Without PC



DSC + PC1



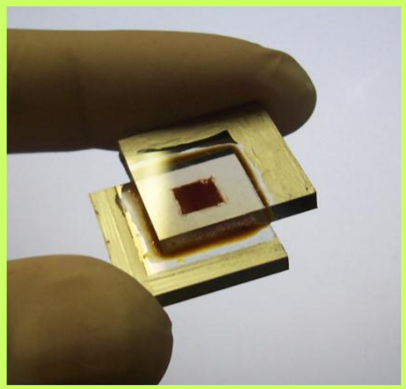
DSC + PC2



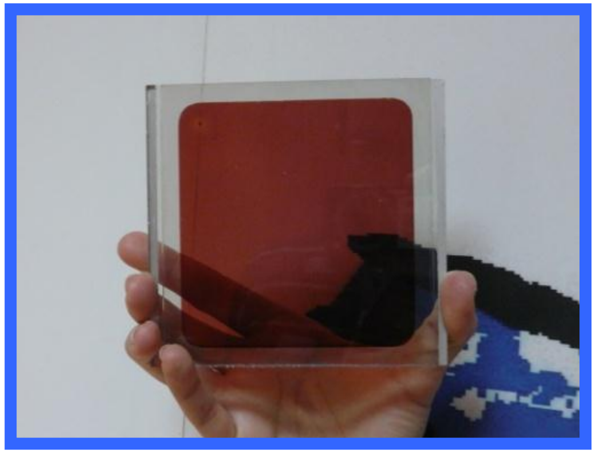
DSC + PC3

From cells to modules
Large Area

From small cell to (sub)module

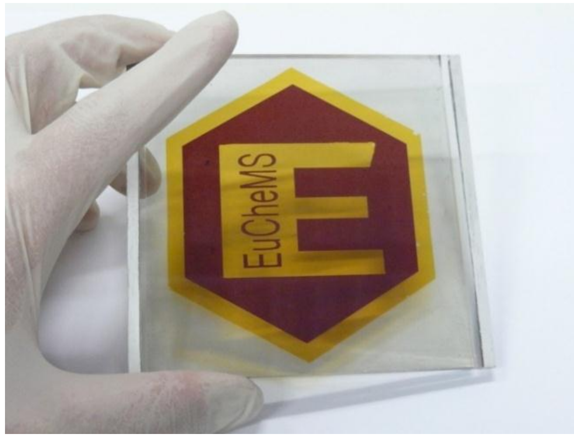


The easiest
(and wrong) way:
simple scale up



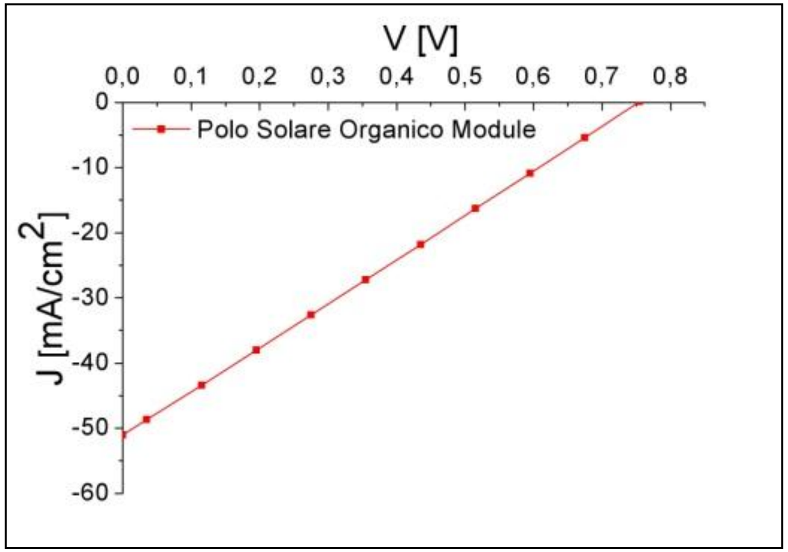
Cell scaling up and colours

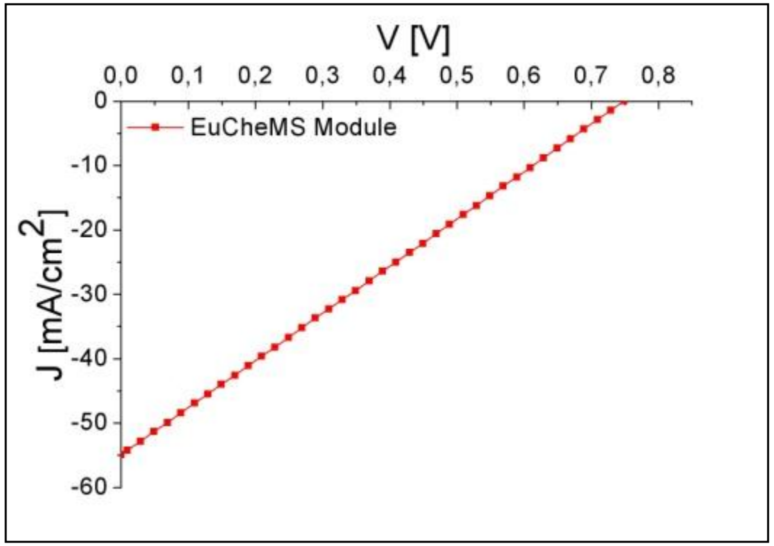
Cells with pattern



Cells with pattern

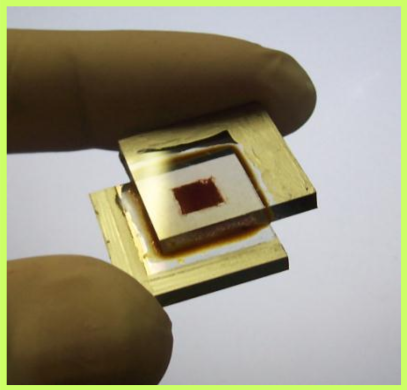
Example of patterned DSC (sigle cells)



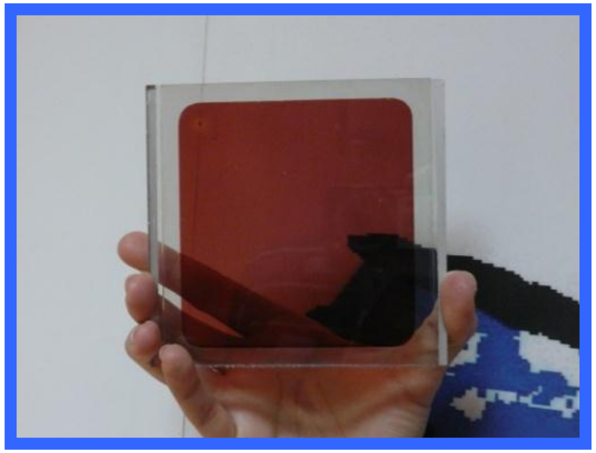


Very Very low efficiency

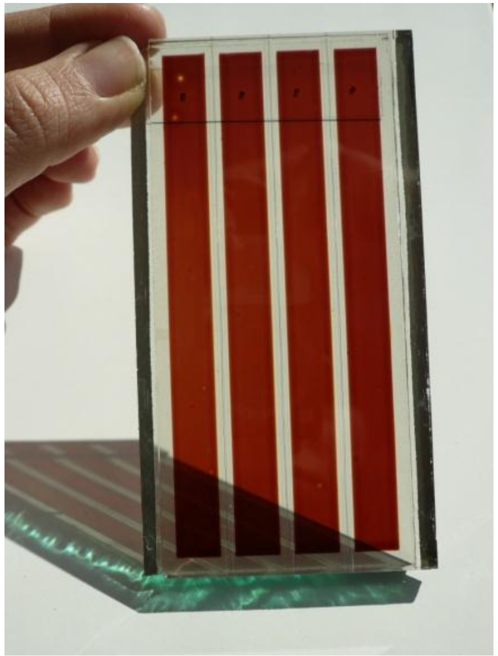
From small cell to (sub)module



The easiest and wrong way: simple scale up

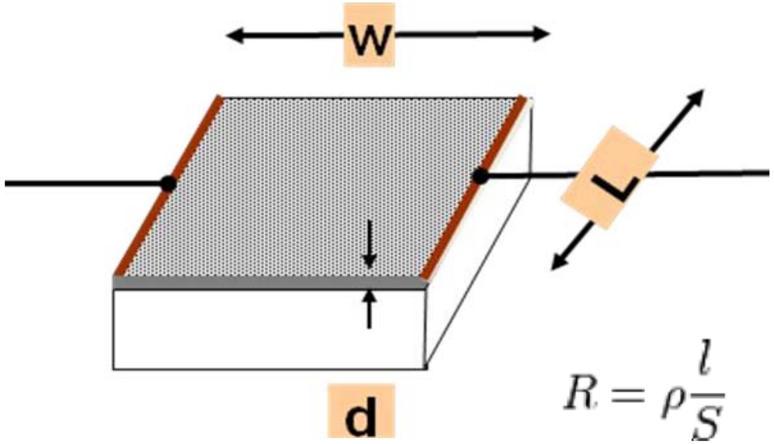


The right way: proper aspect ratio



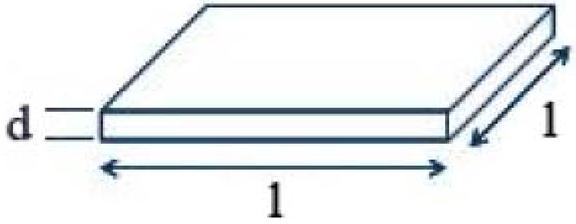
Large area cells: The sheet resistance

Let us consider a substrate (S=LxW) with TCO on top (tickness of TCO = d)



$$R = \rho \frac{l}{S}$$

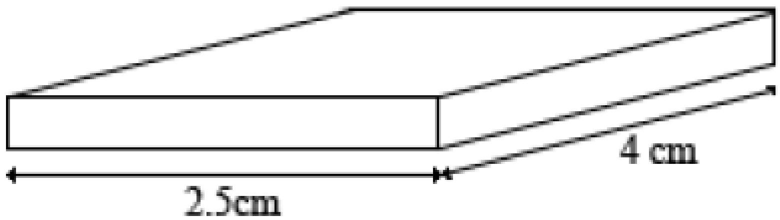
If L=W



$$R = \rho \frac{l}{S} = \rho \frac{l}{dl} = \rho \frac{1}{d}$$

$$R_{square} = R[\Omega / \square] = \frac{\rho}{d}$$ characteristic of the TCO

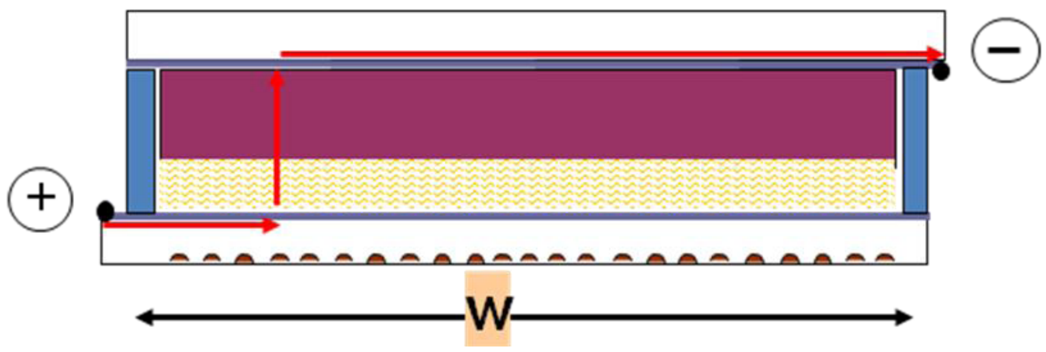
Example



$$R = 8(\Omega / square) * \frac{2.5(cm)}{4(cm)} = 5(\Omega)$$

$$R = 15(\Omega / square) * \frac{2.5(cm)}{4(cm)} = 9.375(\Omega)$$

Sheet resistance influence

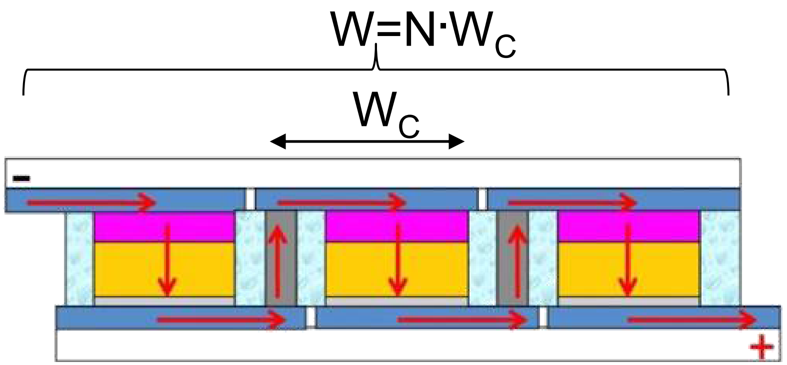


$$\Delta V = RI = \left[\frac{\rho W}{dL}\right]\left[J \cdot L \cdot W\right] = J \cdot W^2 \cdot R_{square}$$

Example (J=10 mA/cm2, R_{square} = 8 Ω/sq):

1) Small area cell (0.5cm x 0.5 cm) = ΔV=0.02V
2) Large area cell (10 cm x 10 cm) => ΔV = 8 V >> V_{oc} !!

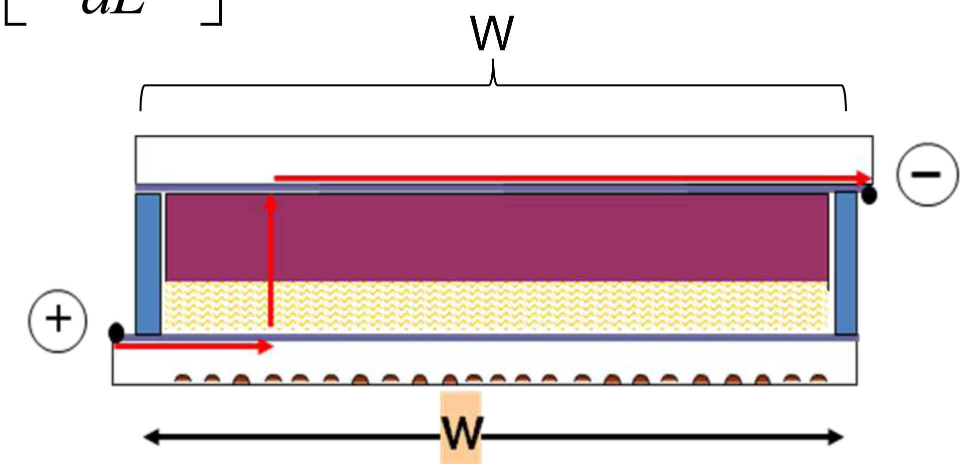
Module with N cells connected in series



$R_{interconnects} = 0$

$$\Delta V_M = RI = \left[\frac{\rho N W_C}{dL}\right]\left[J \cdot L \cdot W_C\right] = J \cdot N \cdot W_C^2 \cdot R_{square} = J \cdot \frac{W^2}{N} \cdot R_{square}$$

Large area cell

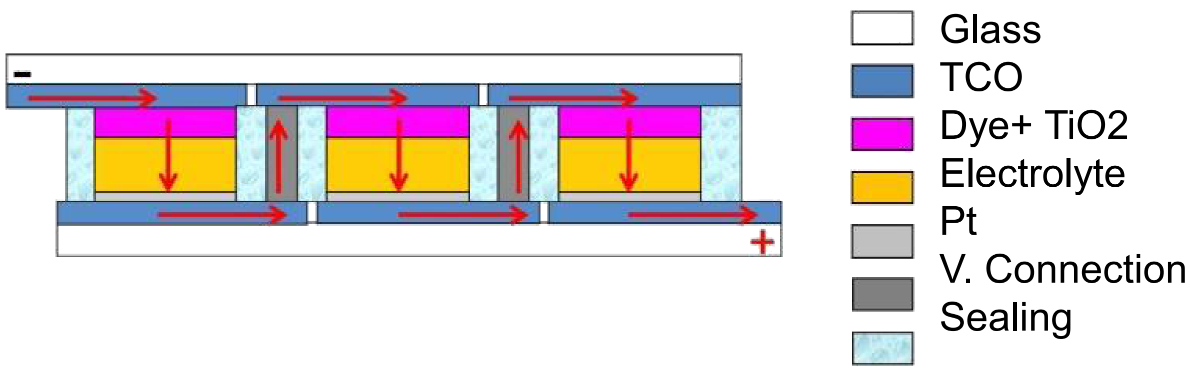


$$\Delta V_M = \frac{\Delta V_{LargeCell}}{N}$$

$$\Delta V = RI = \left[\frac{\rho W}{dL}\right]\left[J \cdot L \cdot W\right] = J \cdot W^2 \cdot R_{square}$$

W and Z schemes

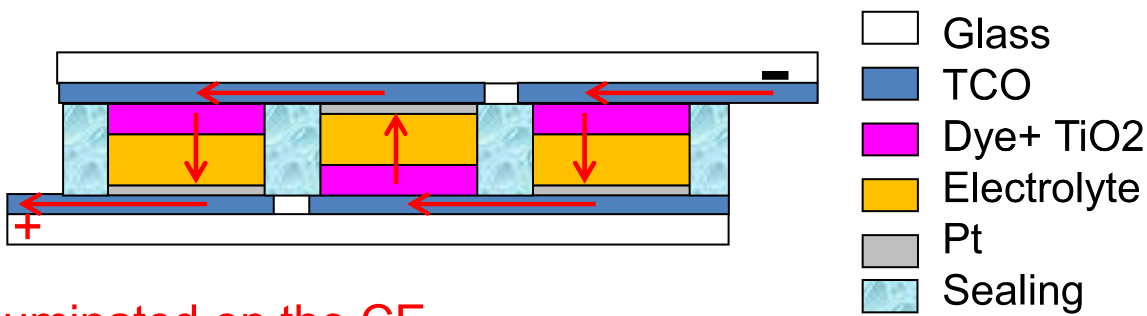
✓Optimized and separated processes for WE and CE substrates



•Vertical interconnections resistance decreases FF
•Sealing more complex
•Lower aperture ratio

Z

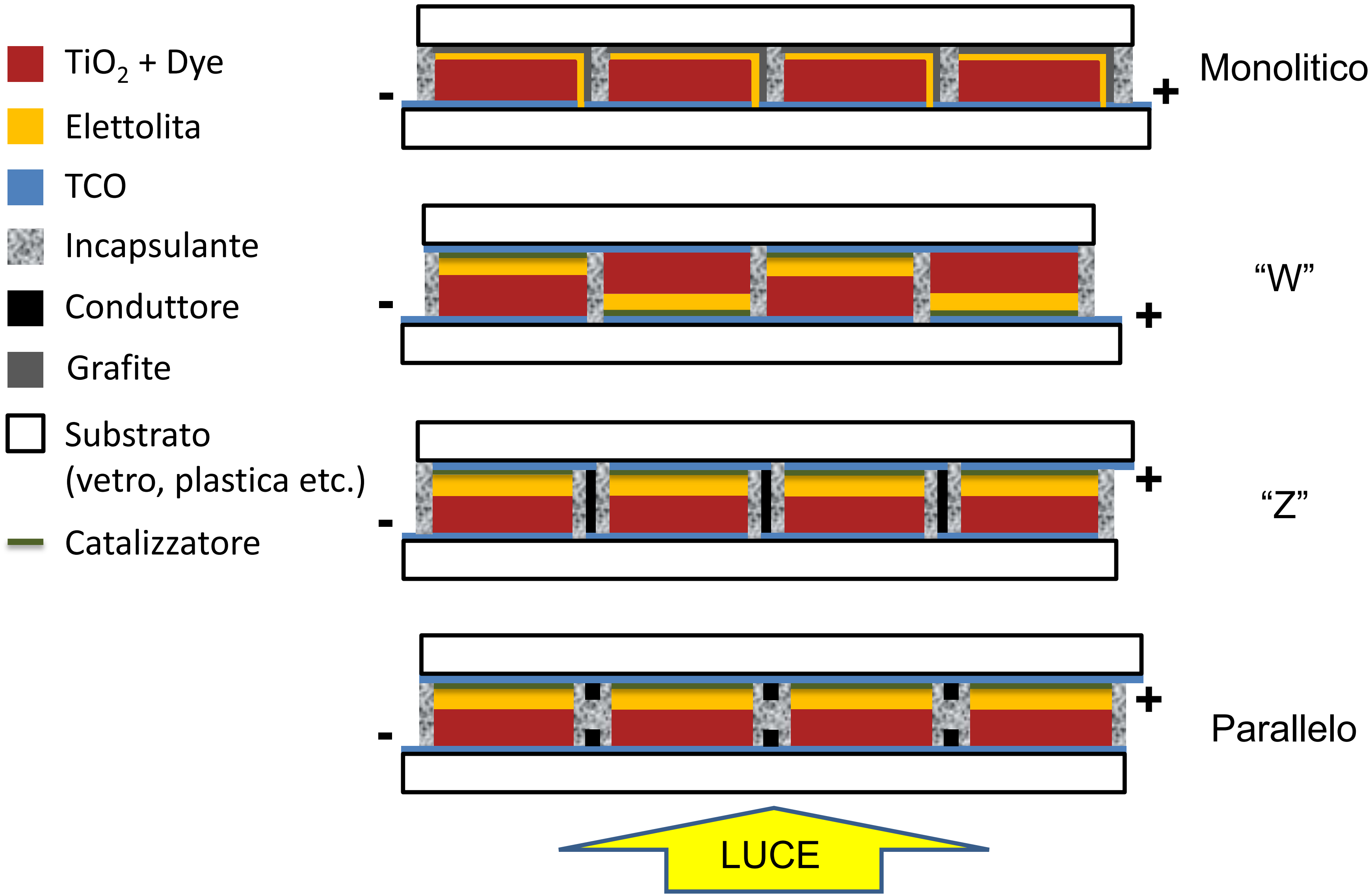
✓No vertical connections
✓High AR



•One half of the cells is illuminated on the CE side(Current matching problem)
• CE and WE processes are on the same substrate

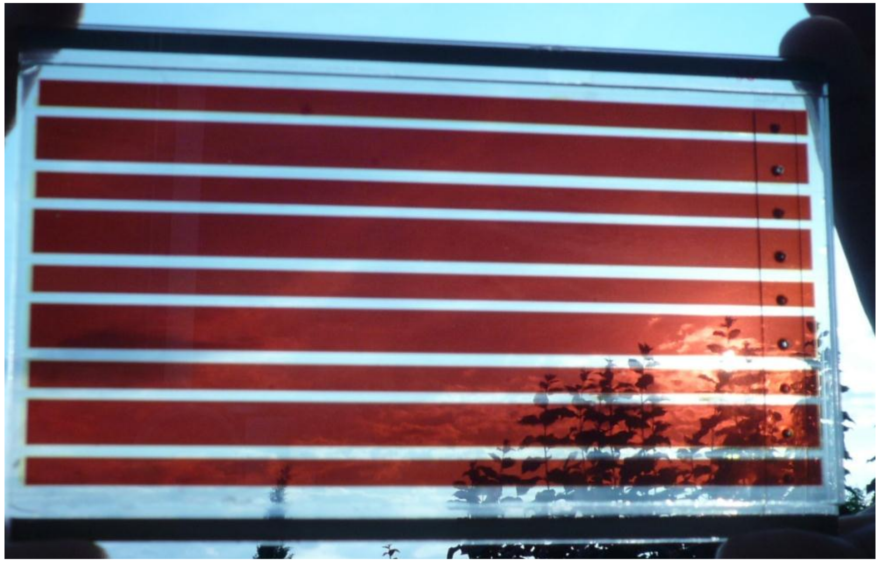
W

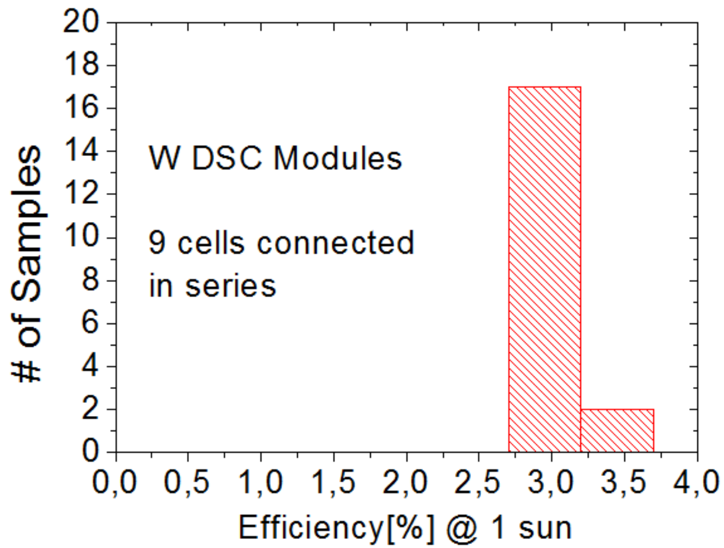
Strutture dei moduli



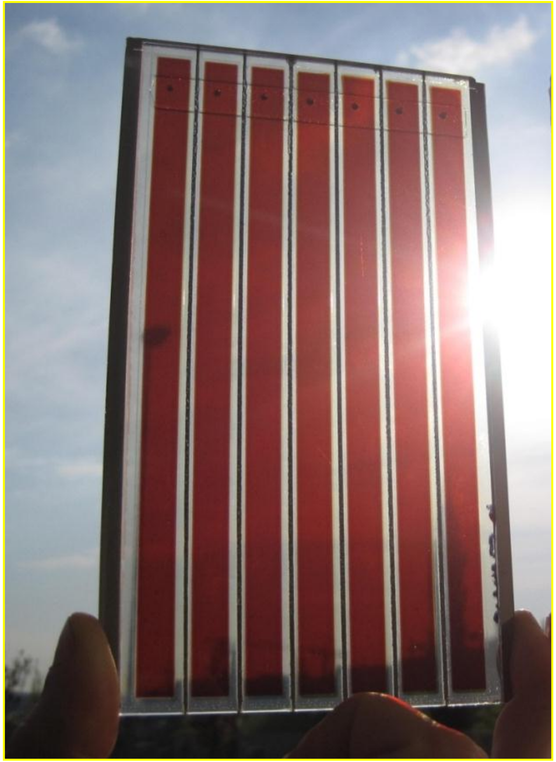
Optimized W module

	N total	Mean	Upper 95%	Minimum	Maximum
Isc [mA]	19	112	115	100	124
Voc [V]	19	5.79	5.83	5.6	5.97
FF [%]	19	53	54.3	48	59
Eff [%]	19	2.9	3	2.9	3.3
Pmax [mW]	19	347	358	317	383

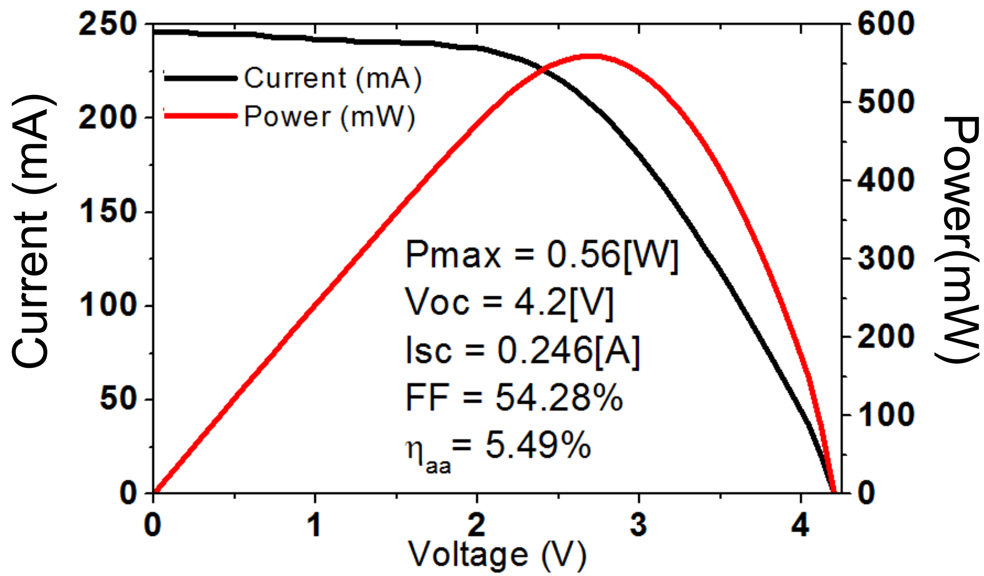




Z module



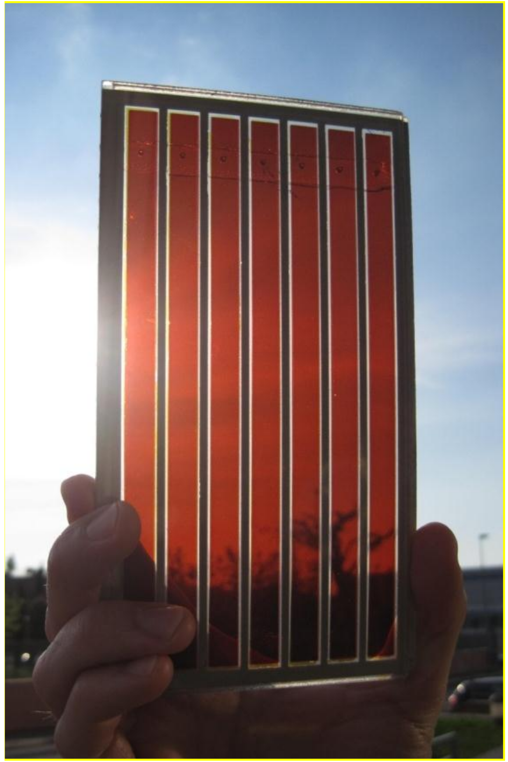
	N total	Mean	Upper 95%	Minimum	Maximum
Isc [mA]	16	236.275	243.537	210	252
Voc [V]	16	4.12625	4.16331	3.98	4.2
FF [%]	16	52.3625	54.13557	43.18	56.96
Eff [%]	16	5.0125	5.2509	3.59	5.49
Pmax [mW]	16	511.1875	535.50473	366	560



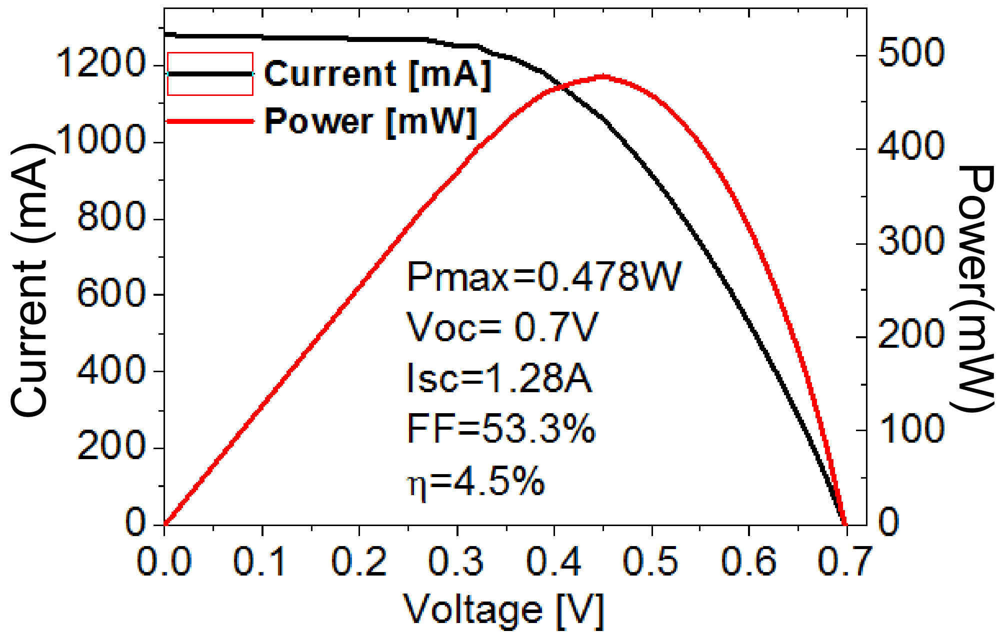
✓ Optimized and separated processes for WE and CE substrates
✓ High Voltage, Low Current

X Vertical interconnections resistance decreases FF
X Sealing more complex
X Lower aperture ratio
X Metal-Electrolyte corrosion

Parallel module



	N total	Mean	Upper 95%	Minimum	Maximum
Pmax [mW]	18	461.25	471.9	426.825	507.93
Eff	18	4.31	4.419	4	4.75

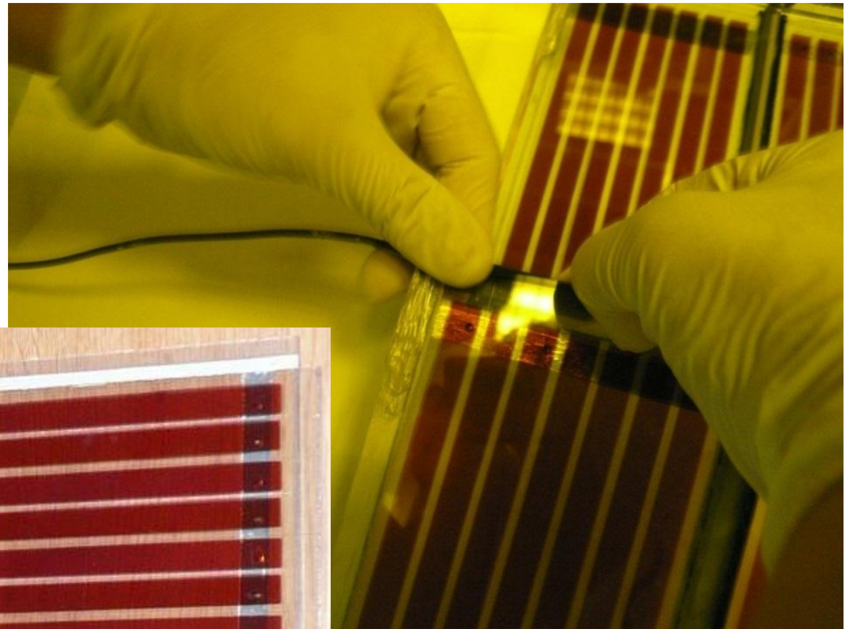


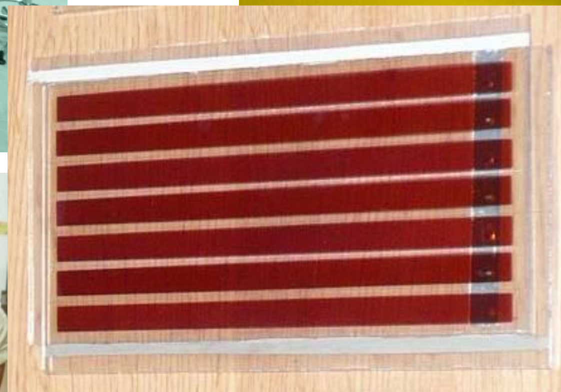
✓ No vertical interconnection
✓ Simpler processes

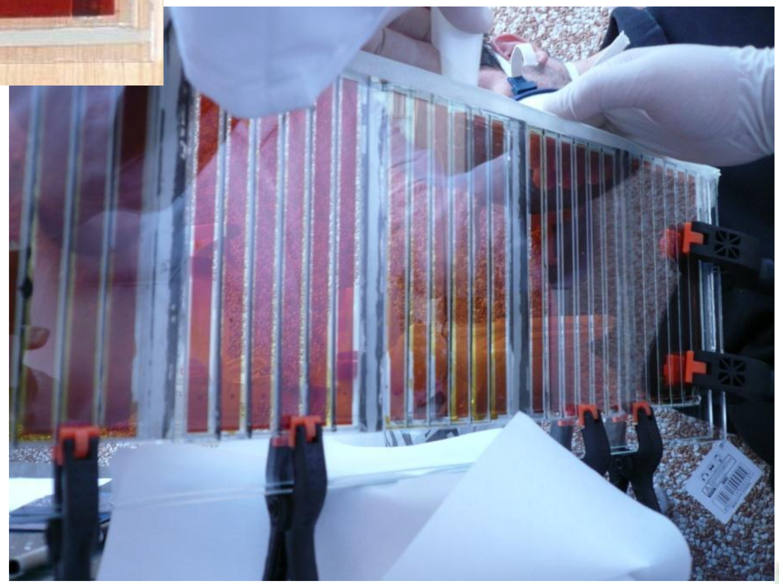
X Low voltage Output
X Metal-Electrolyte corrosion

From Modules to Panels

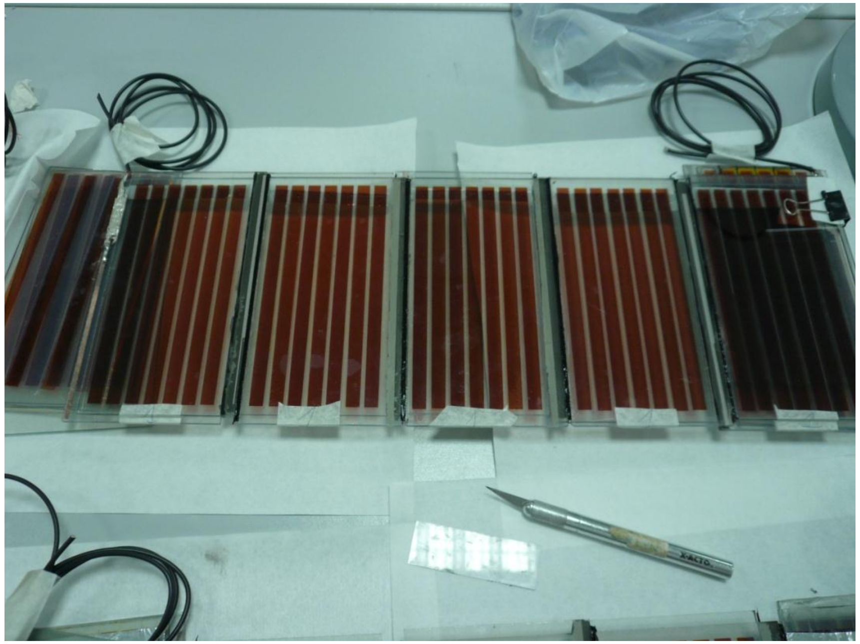
Modules Assembly, bus bar connections

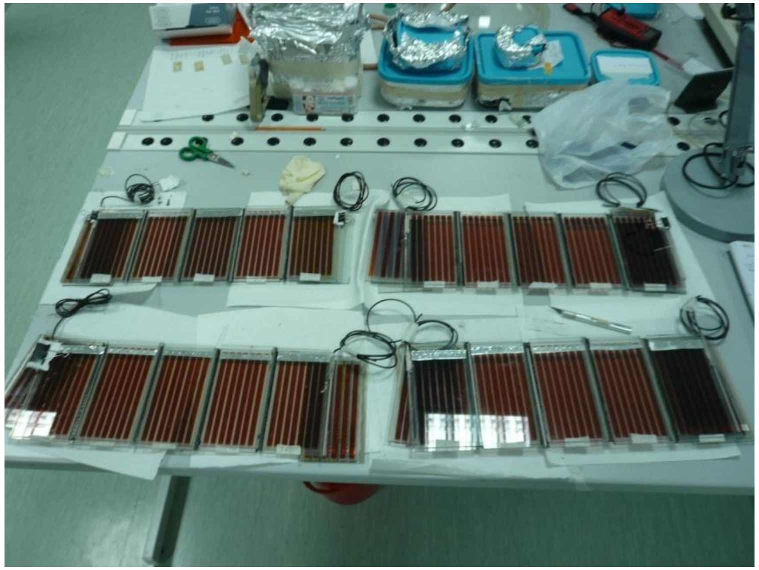


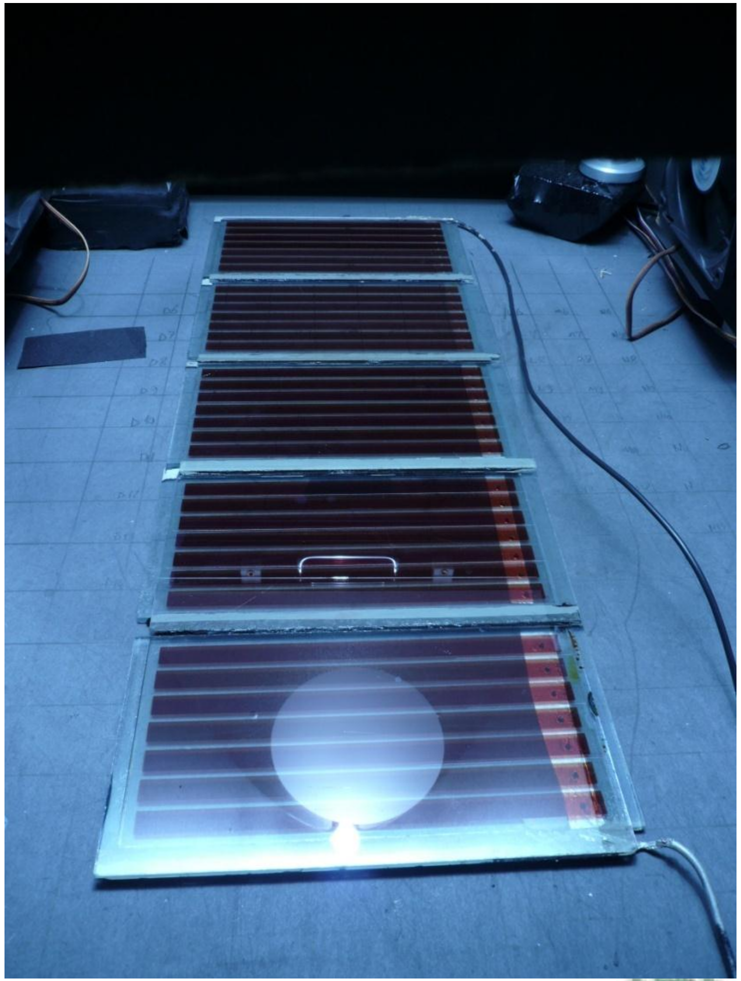




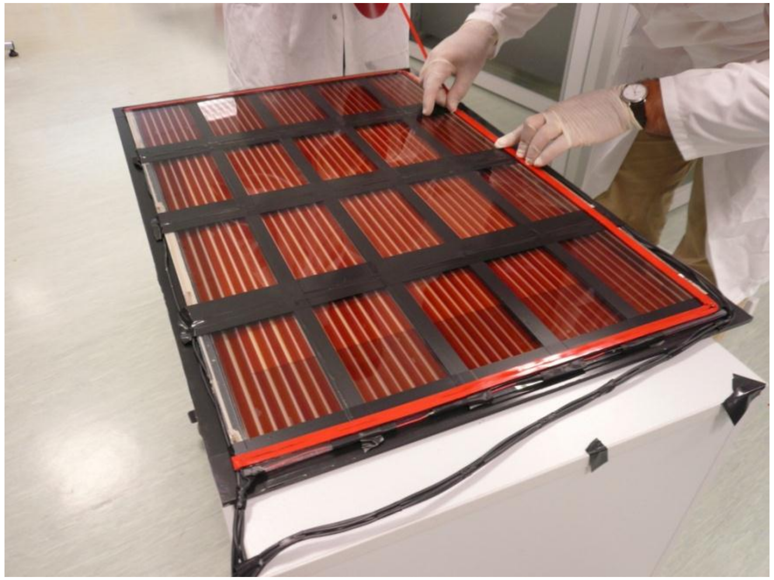
Strings

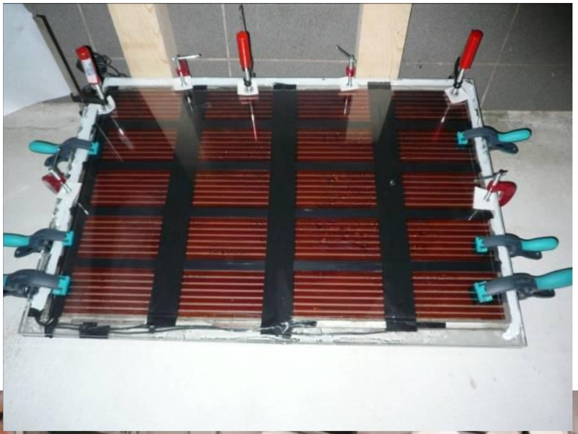


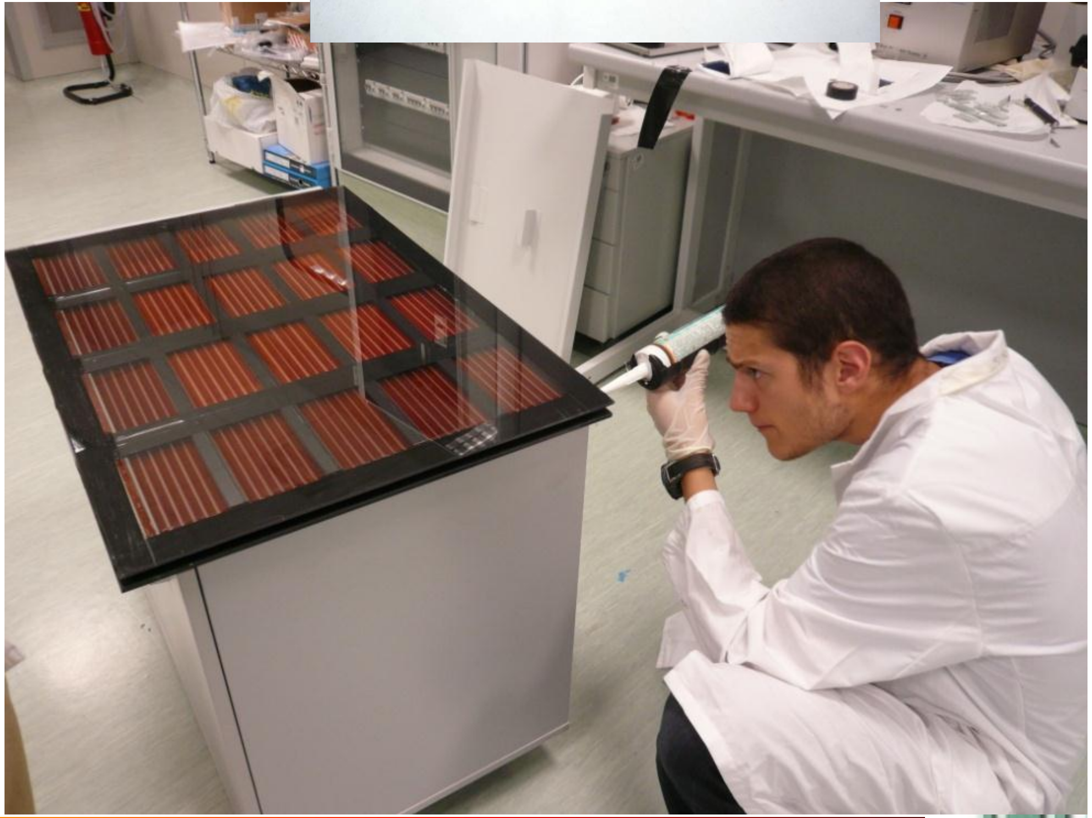


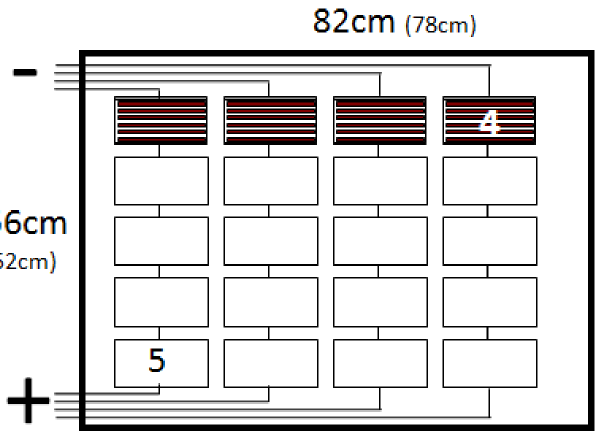


Panel assembly



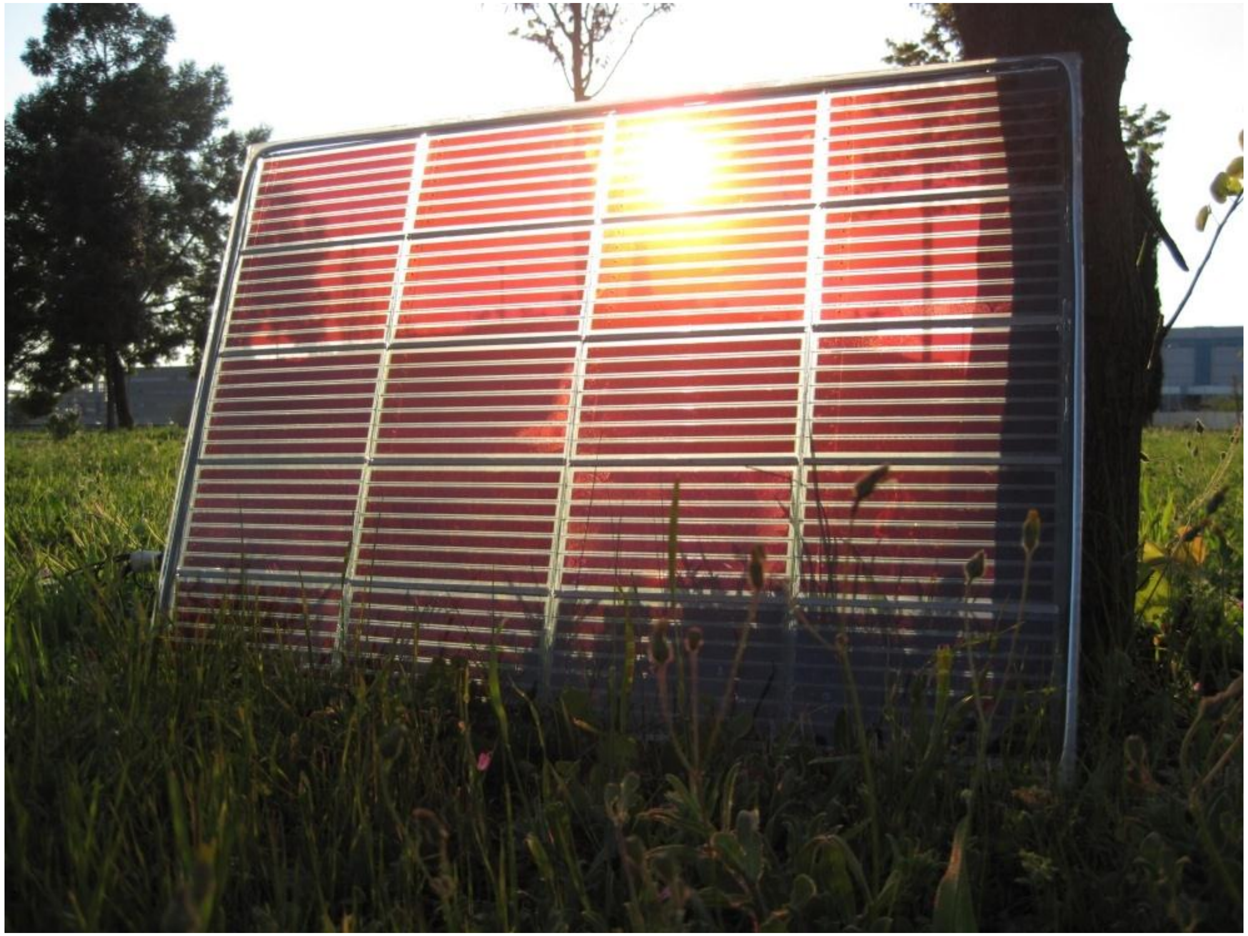






Final panel (August 2009)

Panel v2: April 2010



Outdoor measurements

ENERGIA SOLARE TEST E RICERCA
LABORATORI DI FISICA TECNICA AMBIENTALE
UNIVERSITÀ DEGLI STUDI DI ROMA 'TOR VERGATA'

Outdoor PV Test and meteorological station

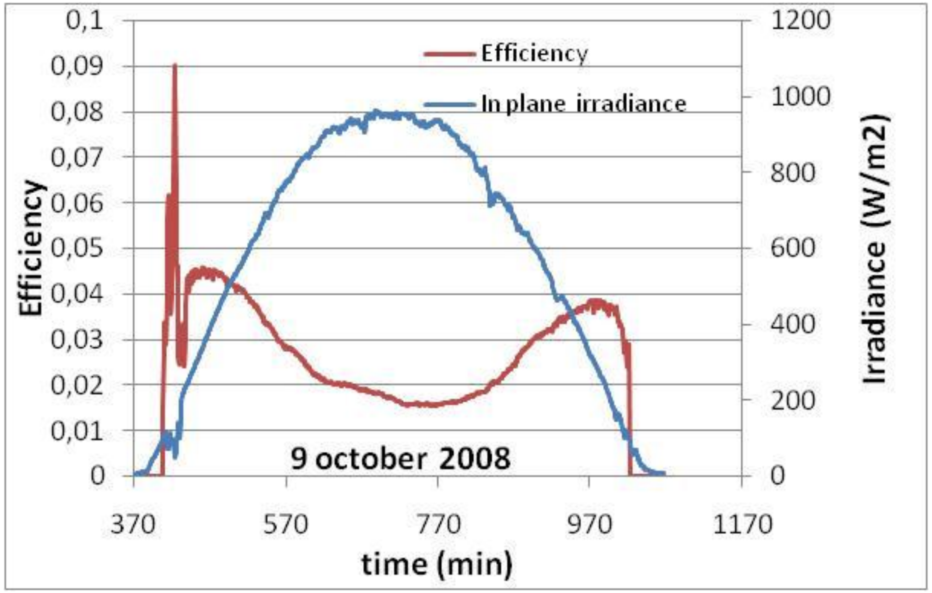
Main Characteristics:
- Meteorological station with also direct/indirect light intensity meas.
- up to 6 panel contemporary measurement with also DSC cell meas.
- 2 rotation axis
- Solar spectra measurement

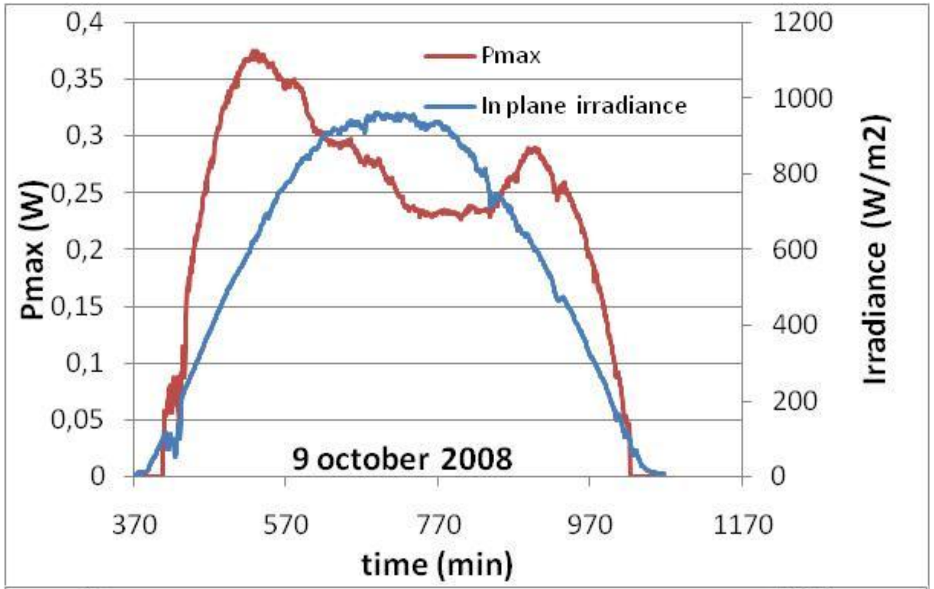
Outdoor measurements

Z panels

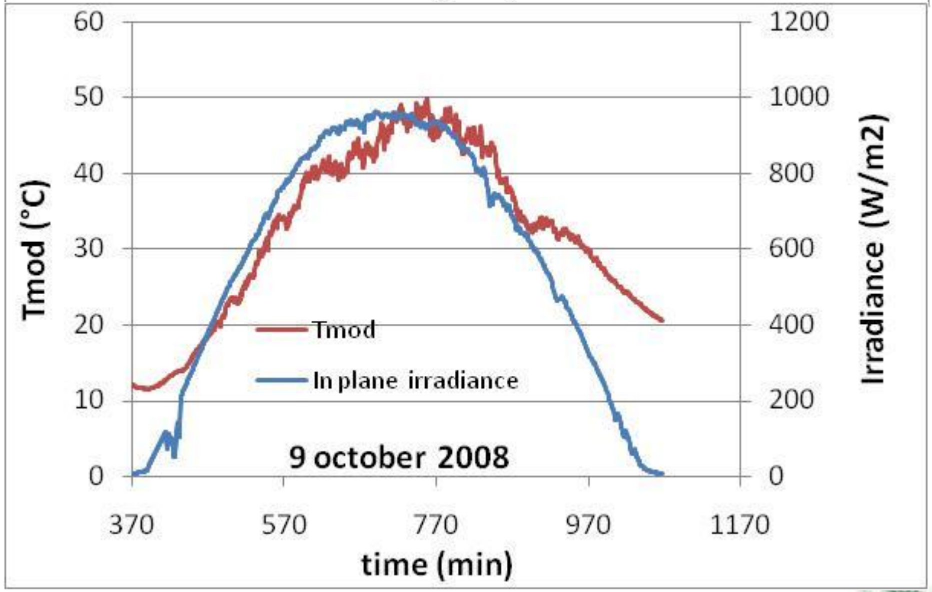
W panel

Outdoor Module test – Clear day

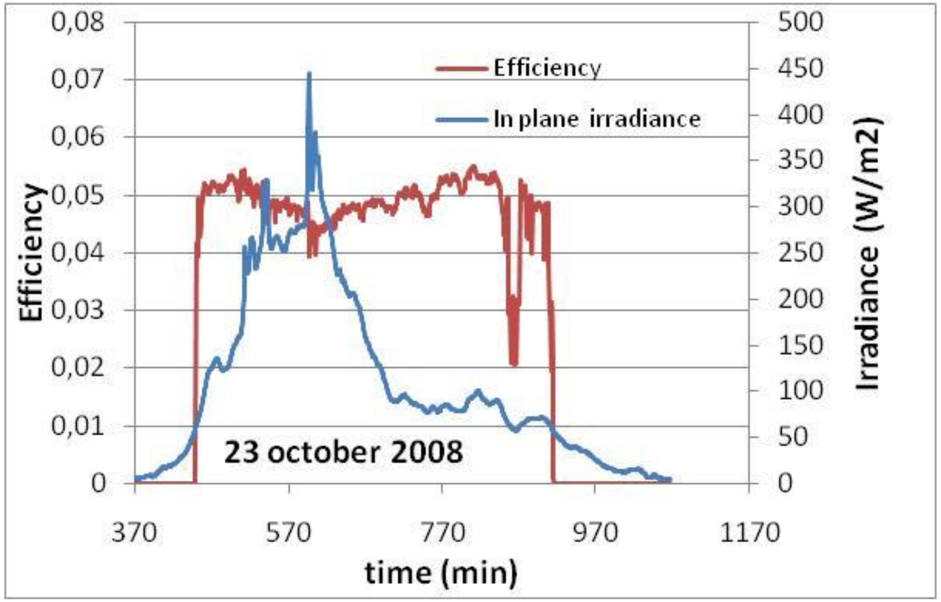


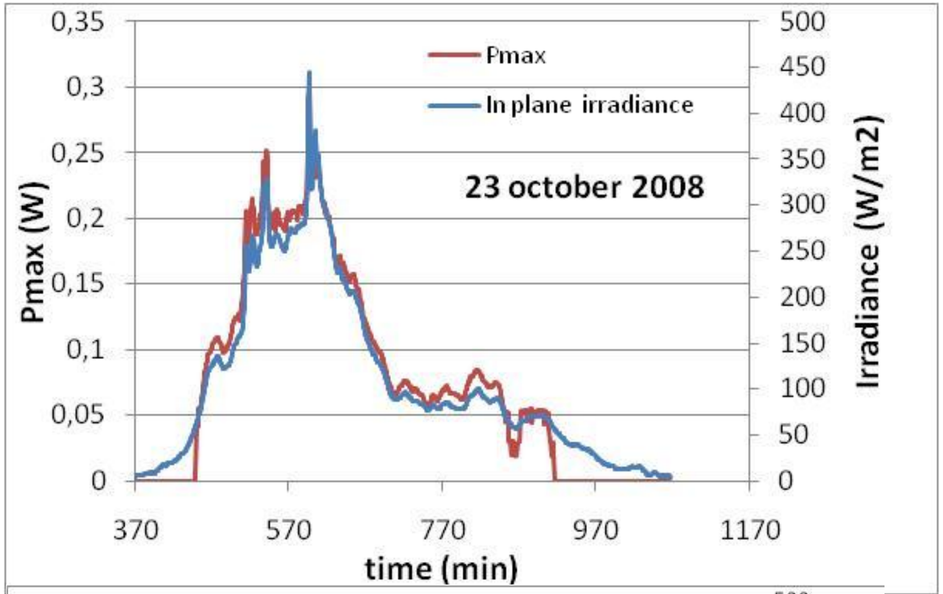


Light is mainly direct

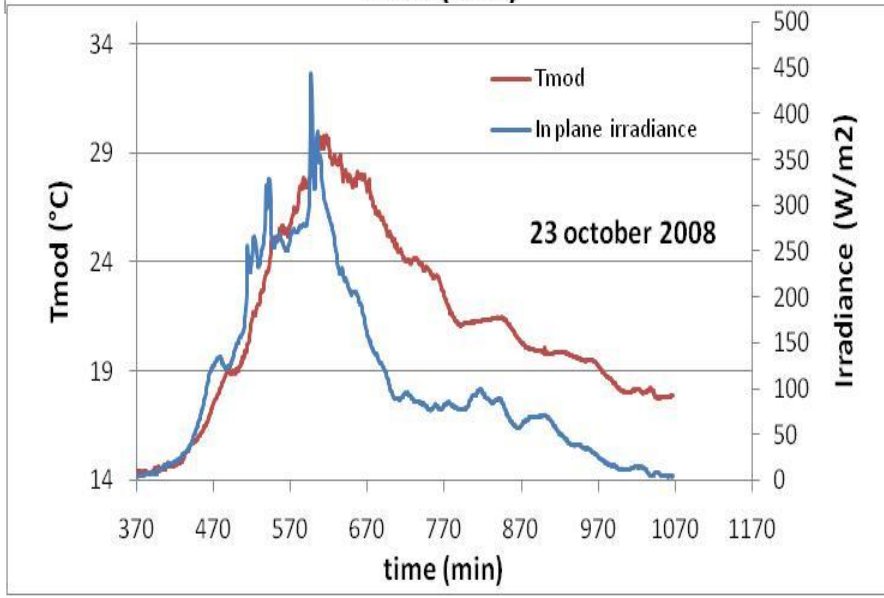


Outdoor Module test – Cloudy day

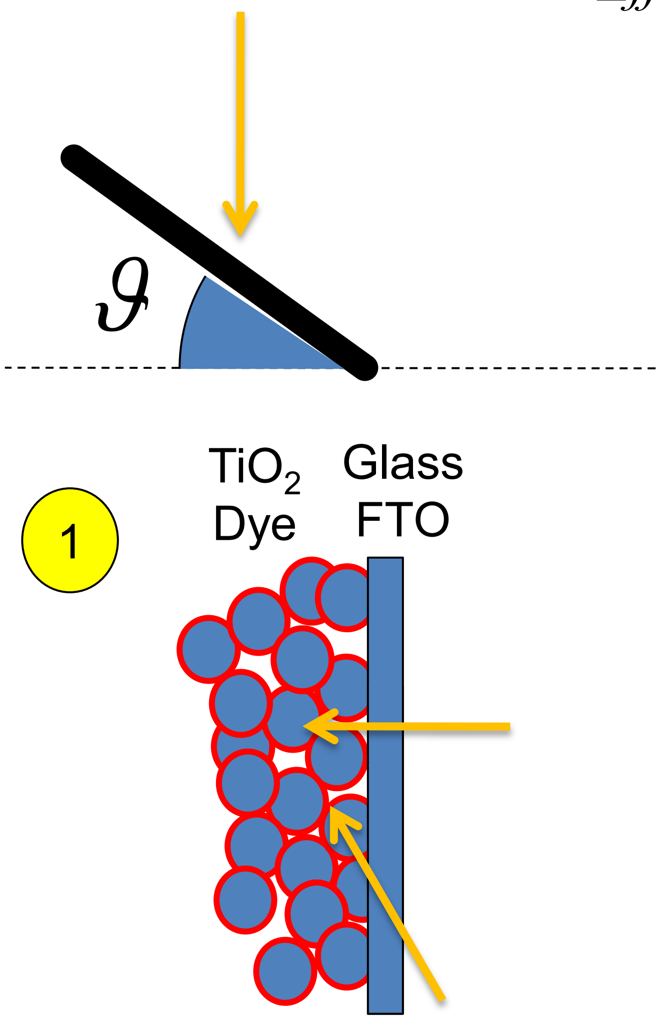


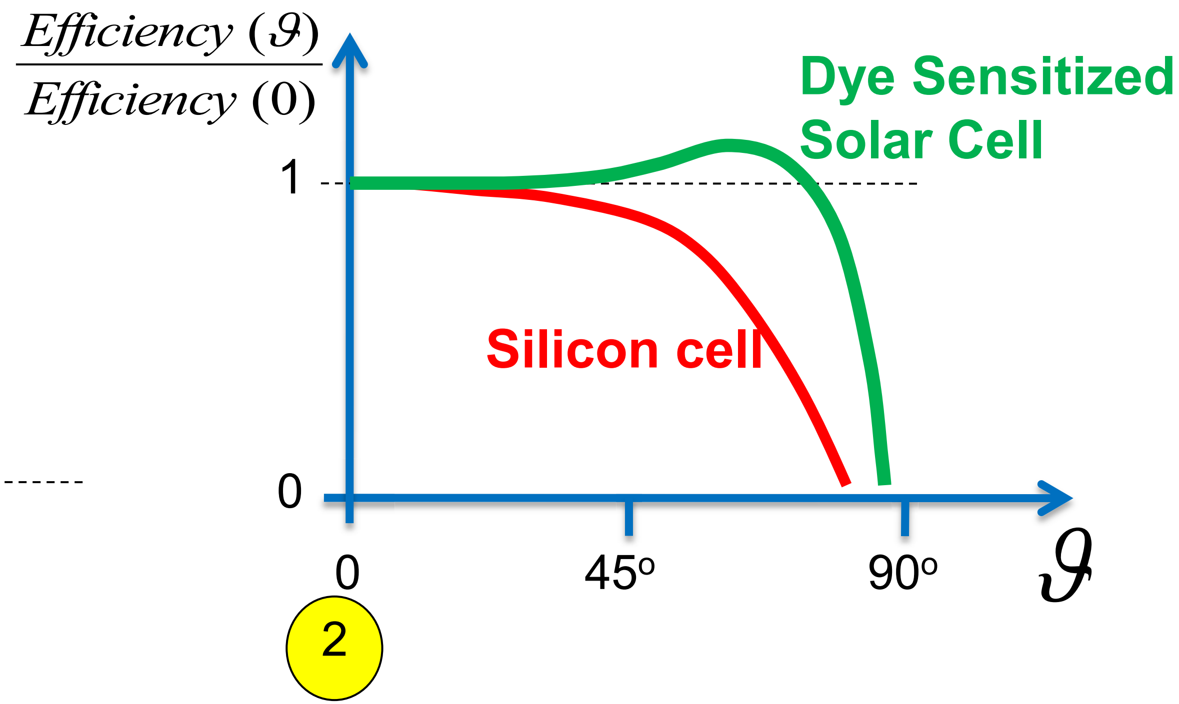


Light is mainly diffused



Angular dependence





Lower is the light intensity higher is the efficiency of the electrolyte to sustain the generated carriers

Path length increases with increasing angle

Build integrated PV

Compared to traditional photovoltaics, DSC has the following differentiation advantages:

Low dependence on angle of light
Stable operating voltage in all light conditions
Natural colours
Optional transparency
Aesthetically pleasing
Manufactured as a building product
Provides additional functionality for energy efficiency

DSSC Façade System
at the CSIRO Energy Centre
Newcastle, Australia - **DYESOL**

Building Integration of Photovoltaics is quite convenient for DSC technology

Facade DSC photovoltaic façade glass can be manufactured
on volume production with low impact on a typical glass façade.

Schott solar

Silicon based PV glass Façade has
50-70 Wp/sqm quite comparable with DSC !!!!!

A continuous Glass Façade WITHOUT PV costs 1000 euro/sqm

Applications (Sony)

Acknowledgments

- UniFerrara (Bignozzi team)
- UniRoma 1 (Decker team)
- UniTorino (Viscardi-Barolo team)
- DYESOL

Tor Vergata team

www.chose.it

REGIONE LAZIO

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M. Liberatore
A. Gagliardi
A. Lembo (Dyesol)
T. Denaro (Dyesol)

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Conclusions

- DSC represents a new way for silicon free photovoltaics. Large tunability, easy manufacture, low plant and material costs.
- Large area devices is not trivial and many issues are still open
- Industrialization is very close
- Scale up of the materials with price reduction is request.
- Many applications. DSC is well suited for building glass envelopes