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DSC: Production, applications and market opportunity

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DSC: Production, applications and market opportunity

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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:

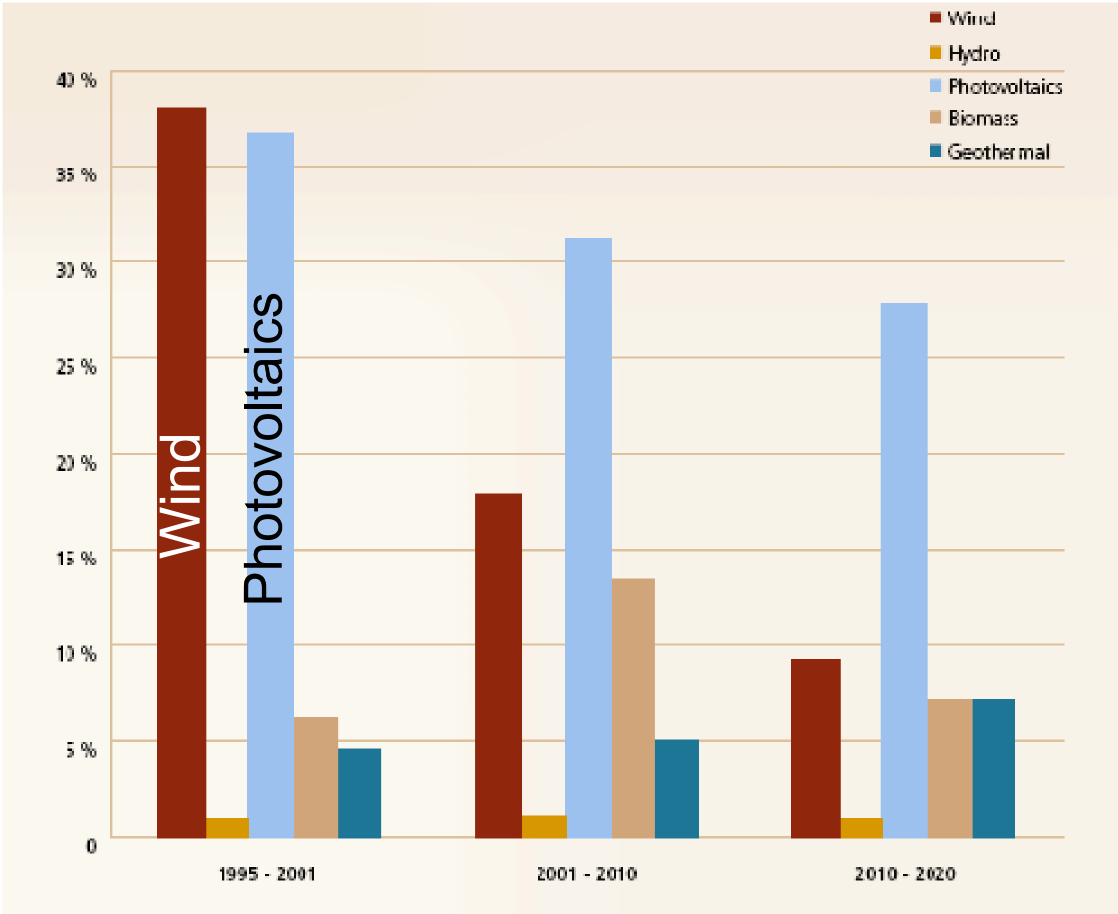
- 443 billion euro investment 2001-2020
- 115.8 billion euro gained from fuel reduction
- 130 - 320 billion euro gained from additional costs
- 2 milioni additional jobs

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).

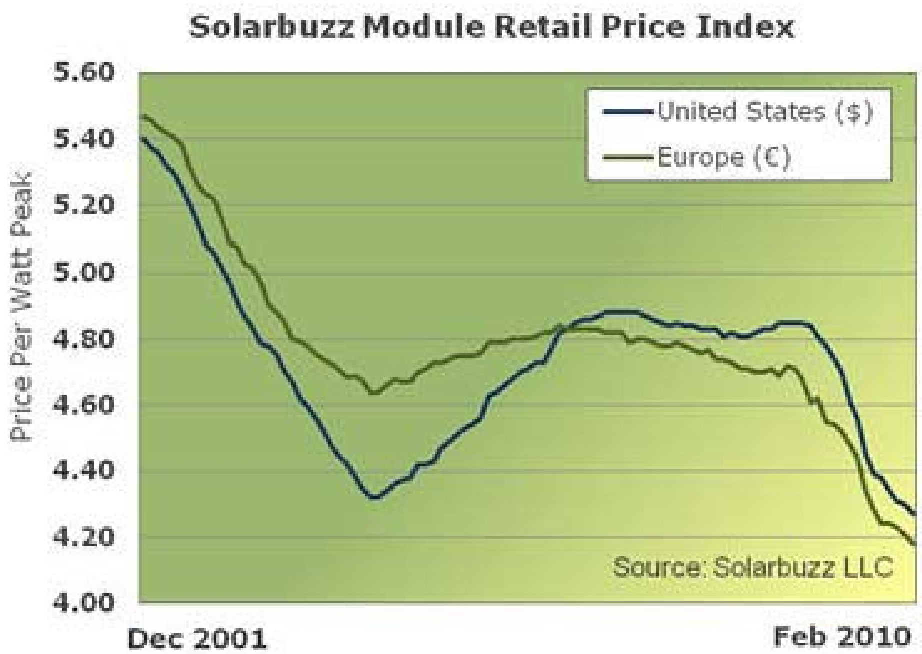
EPIA considers the DSC as the most mature amongst the OPV technologies and thus pushes for a decisive plan for its research and development that can deliver the first production lines in the near future.

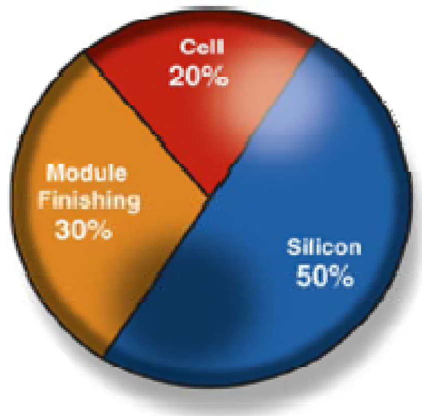
Energy from the sun

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 → 20.000 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) ?

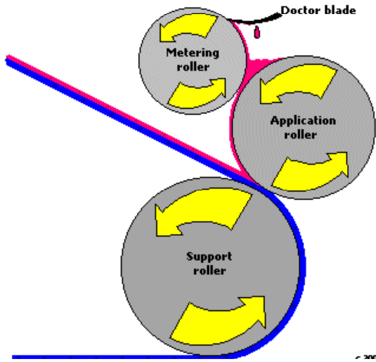
This is possible but we have to re-invent the cells and the fabrication processes

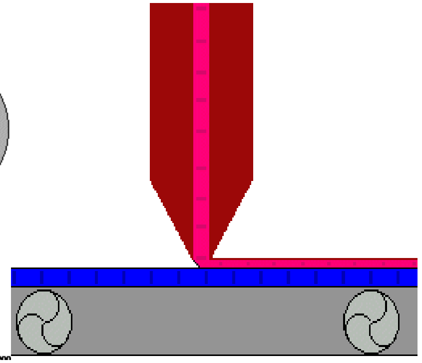
→ **Organic photovoltaics**

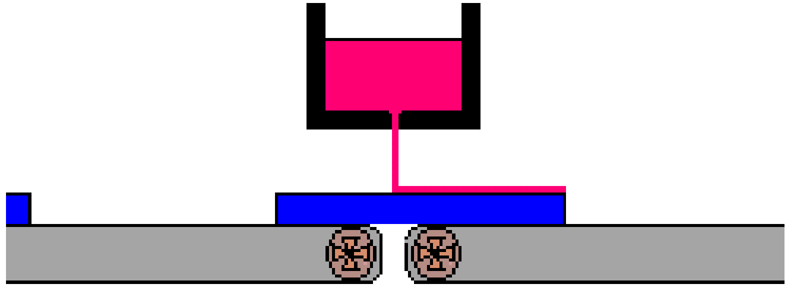
“New” manufacture processes

Conventional Electronics → **Organic Electronics**

Conventional semiconductor industry → **Printing methods**



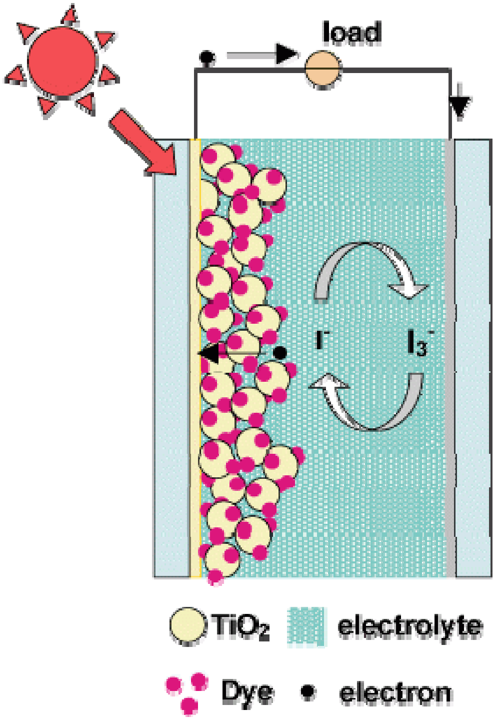


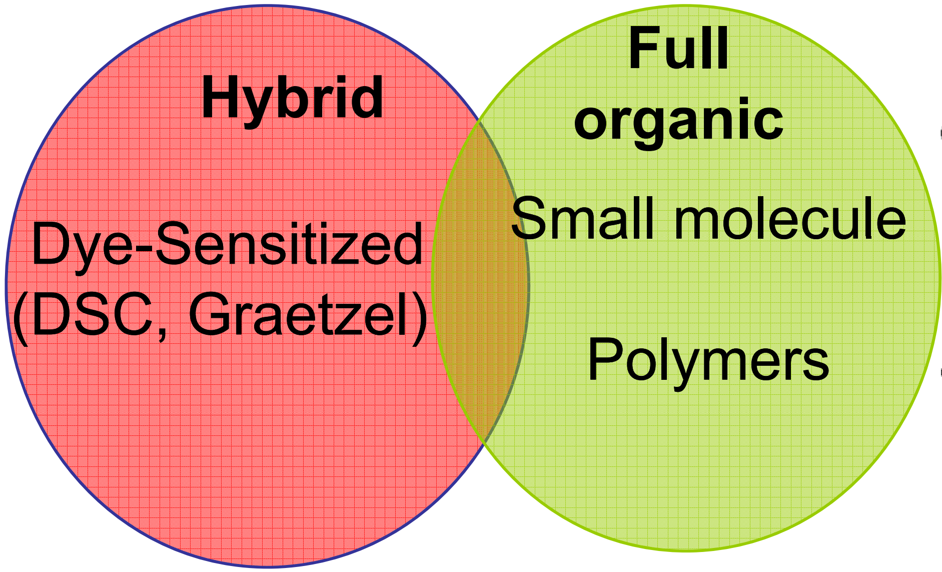


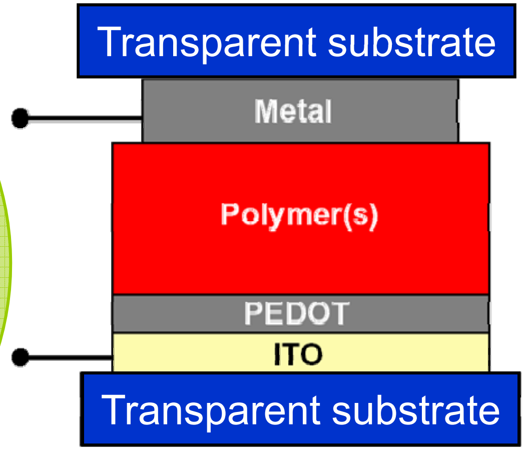
High temperature, doping, vacuum → **Liquid deposition**

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

Organic photovoltaics

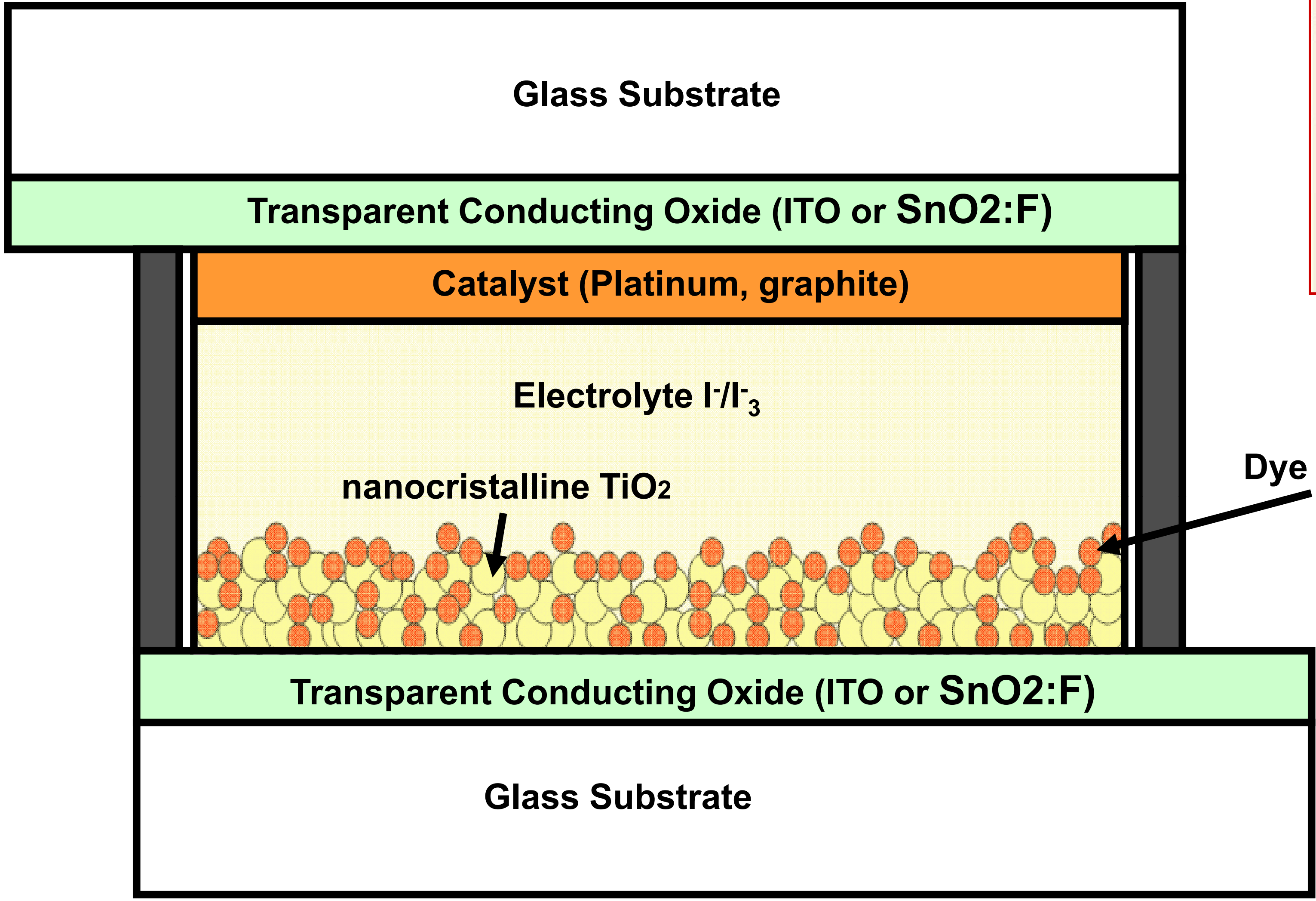


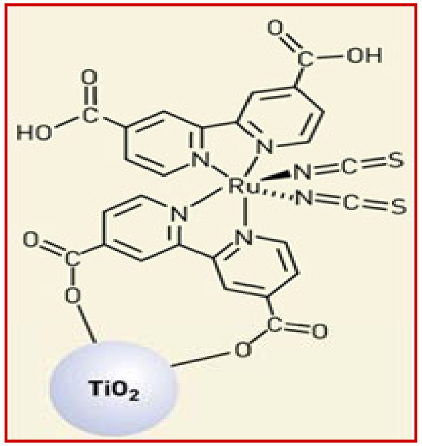




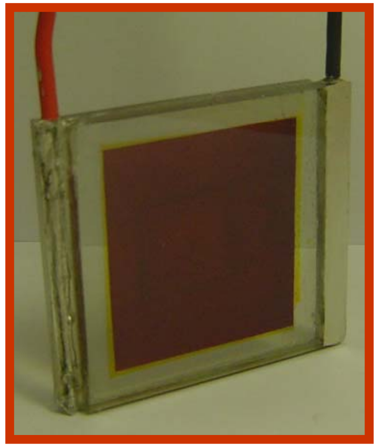
Type	Max lab efficiency	Stability	R&D
Hybrid Dye Sensitized (Graetzel)	~ 11-12%	20 years	University and industry
Full organic solar cells	~ 5%	3 years	University and industry

Structure of Dye Sensitized Cells

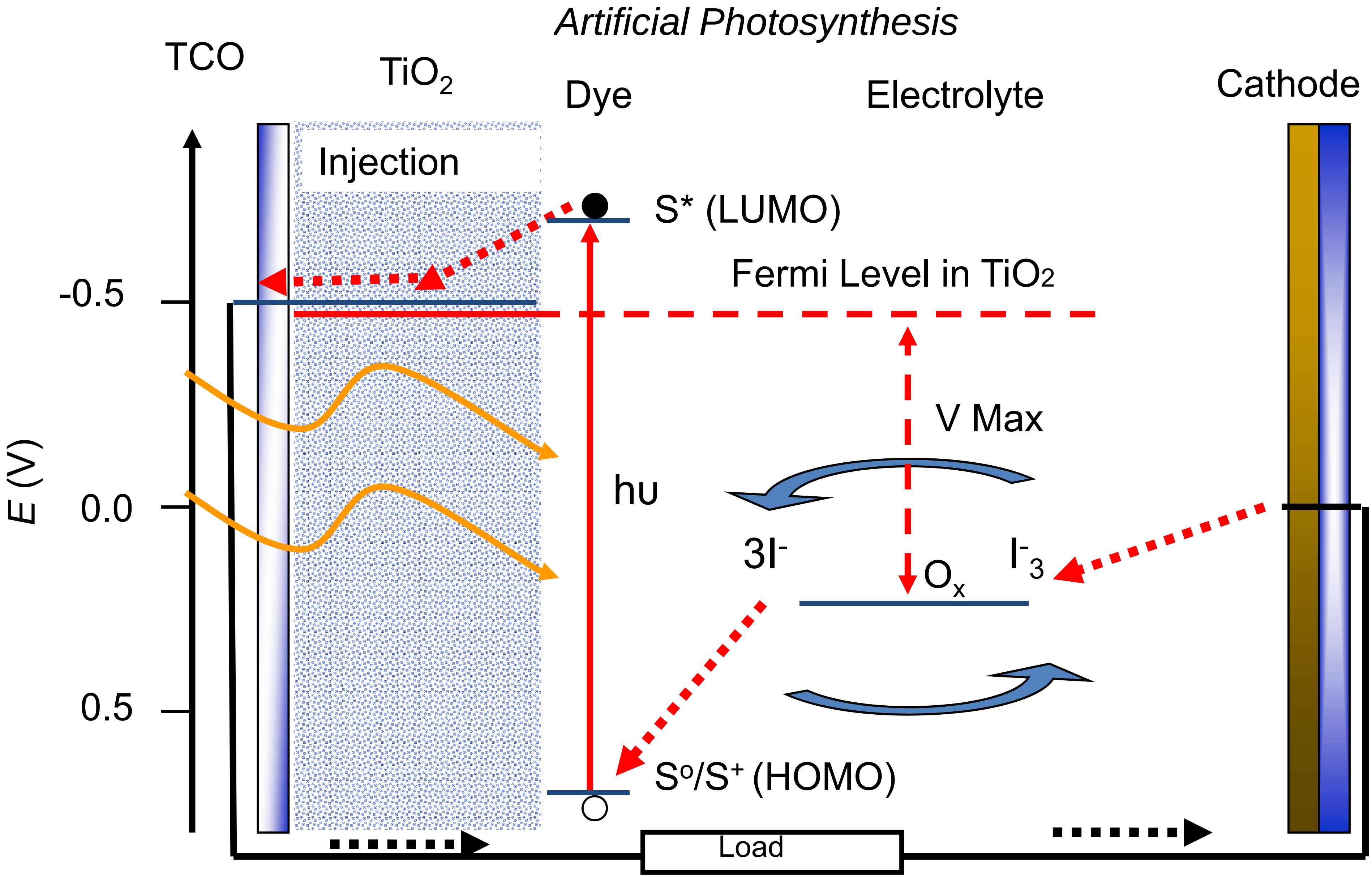




Dye Molecules on TiO2



Working principle of DSC



No permanent chemical transformation in the materials composing the cell

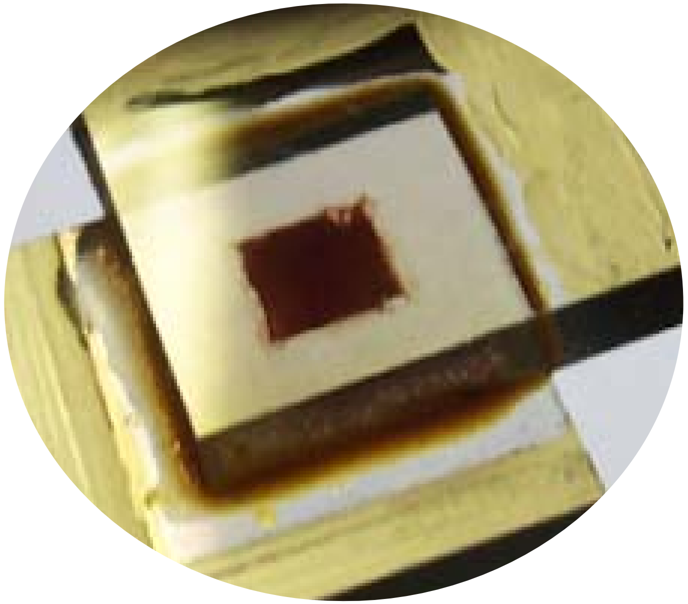
Cell optimization

Optimization parameters

(an engineer view)

TiO_2

Dye



Electrolyte

Couter-Electrode

Encapsulation

Layout

Printing Technique

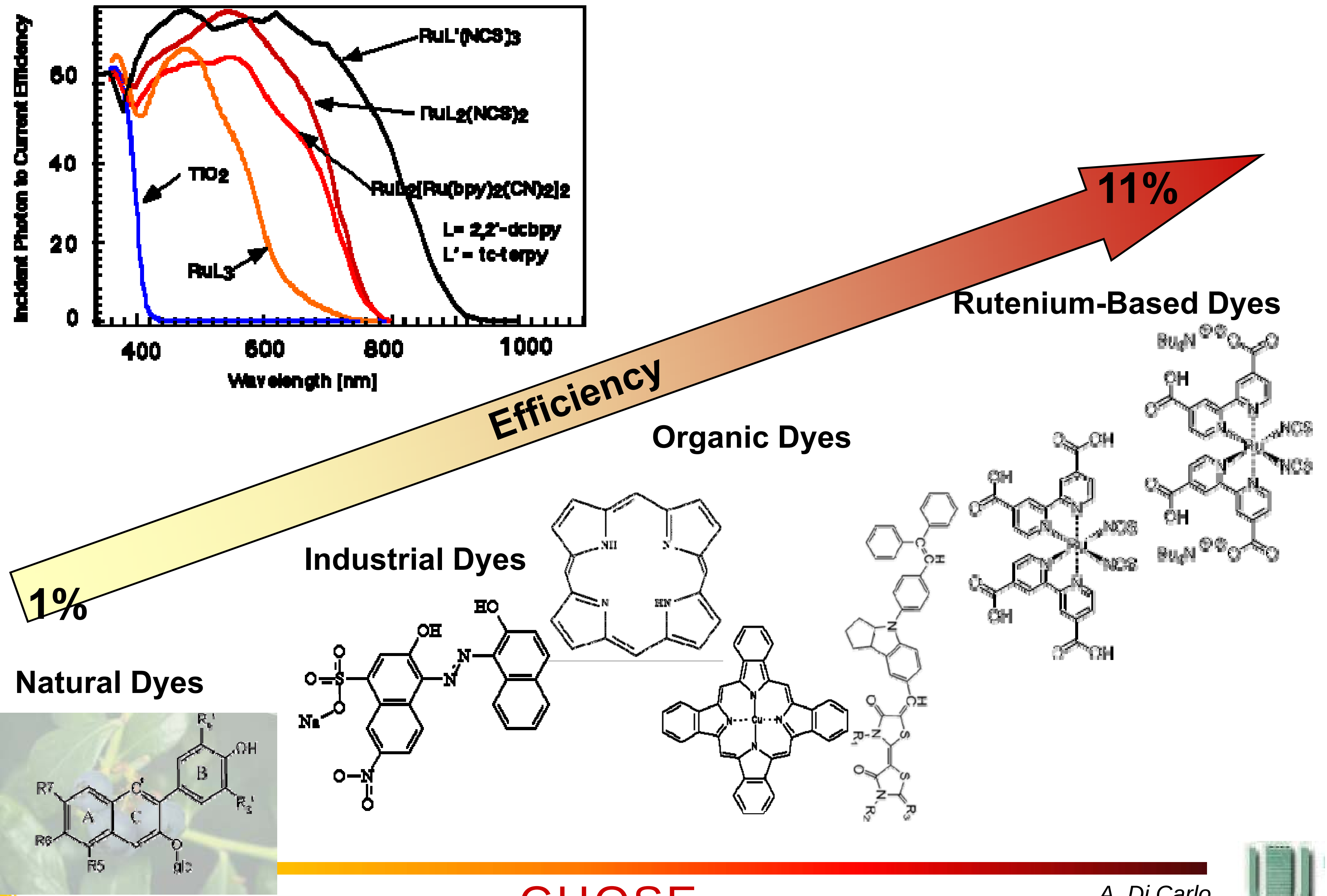
Easy

Mediu
m

Critical

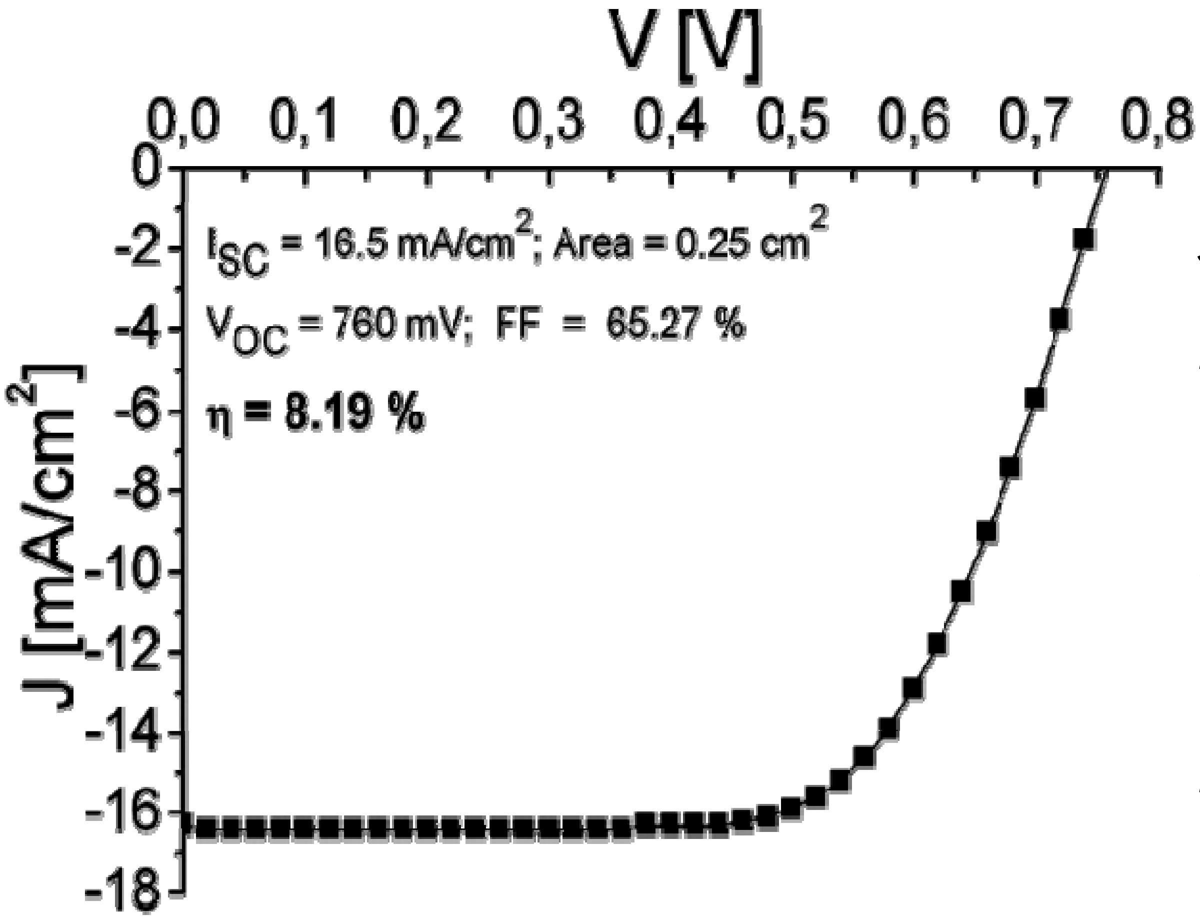
Difficult

Dyes



Incident Photon to Current Efficiency
0
20
40
60
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*

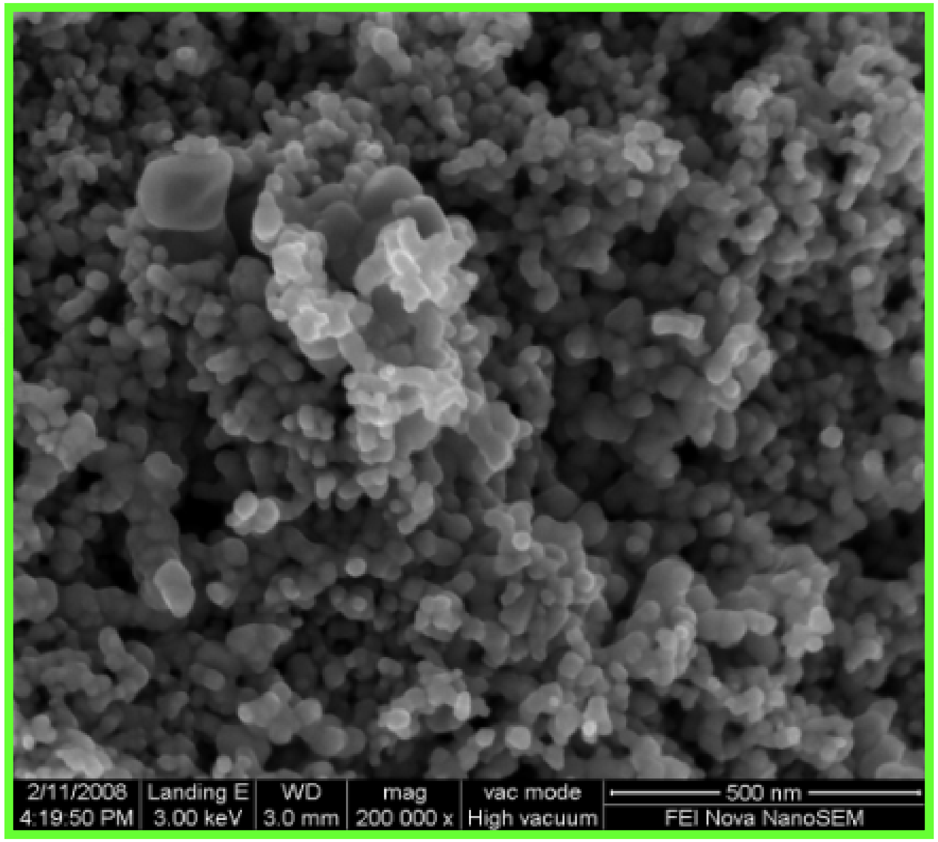
  fired 400°C @ 5'

- ✓ *Spacer Surlyn 60 μm*
- ✓ *Electrolyte Dyesol HPE*

Process Improvements 1/2

Introduction of $TiCl_4$ treatments

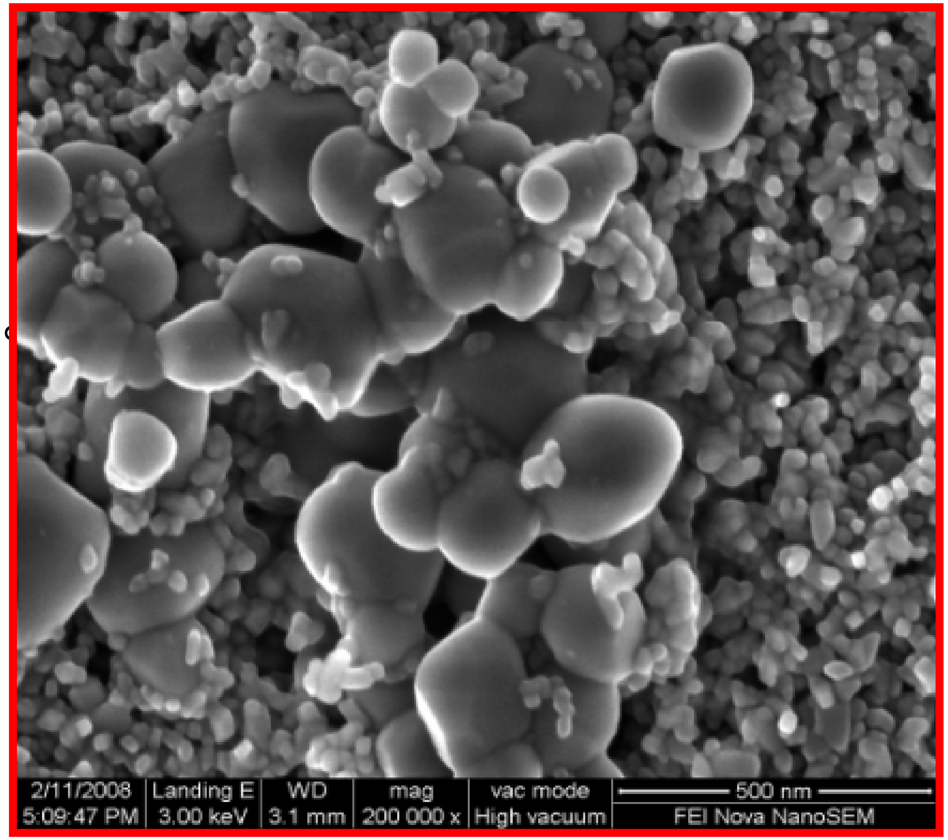
Pre TiO_2 deposition + post sintering treatments
$TiCl_4$ solution 40mM 30’ @ 70°C



Transparent

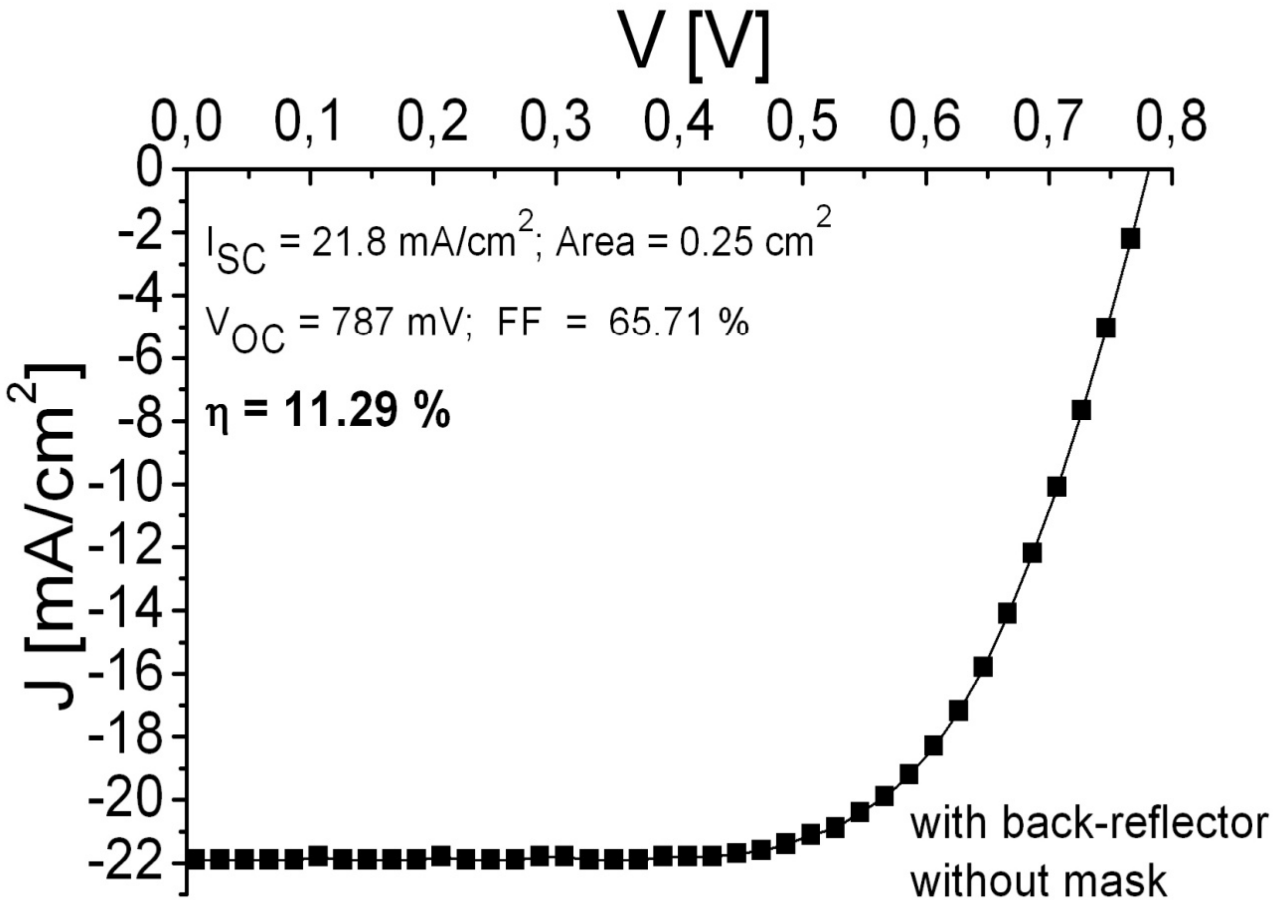
Introduction of scattering layer

TiO_2 Dyesol scattering paste WER4-0
Thickness 8 μm*



Not Transparent

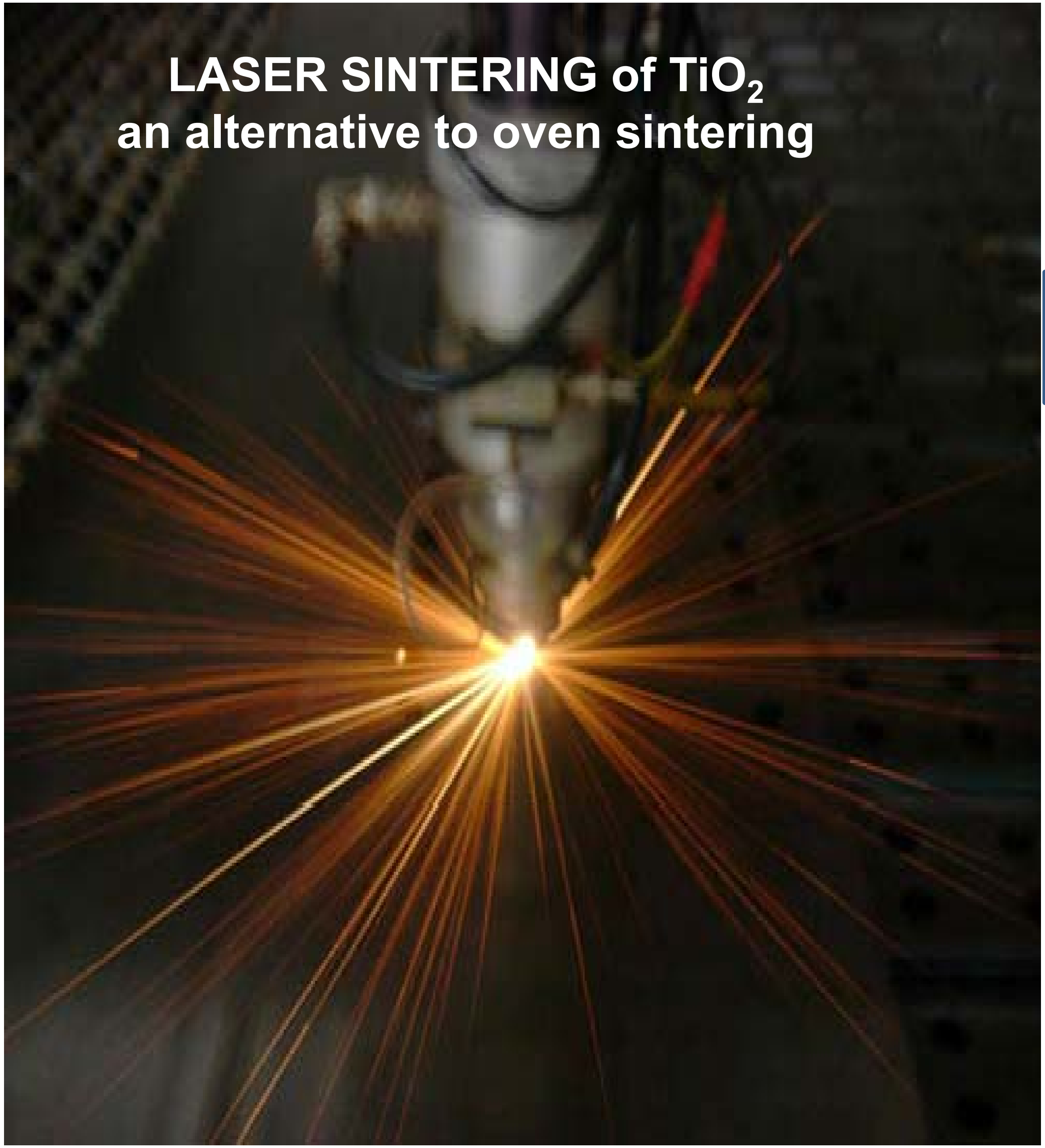
Process Improvements 2/2

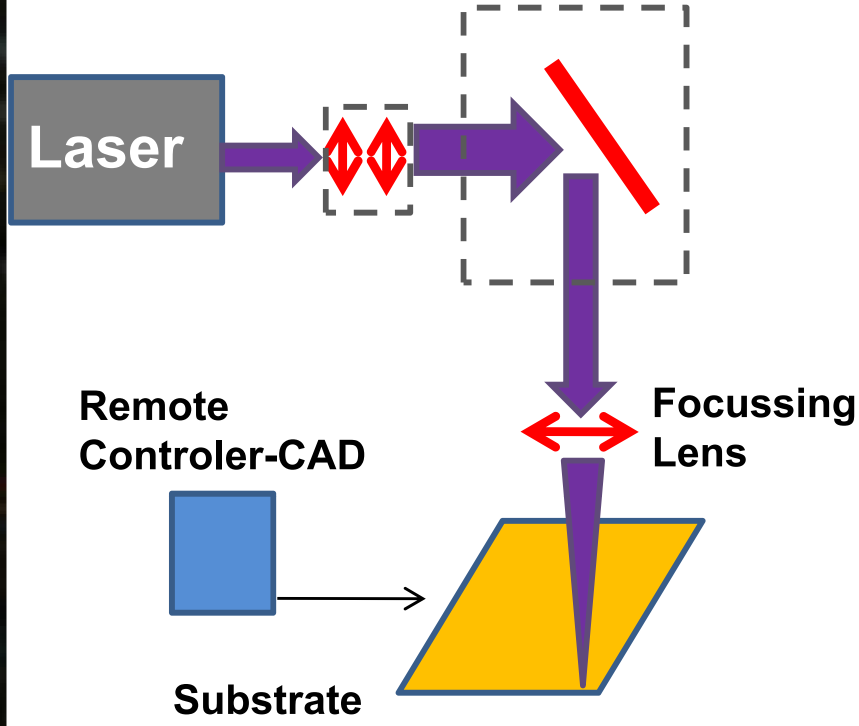


I/V Characteristics of the $TiCl_4$ treated cell measured with the introduction of back-reflector

Good reproducibility within 2% deviation

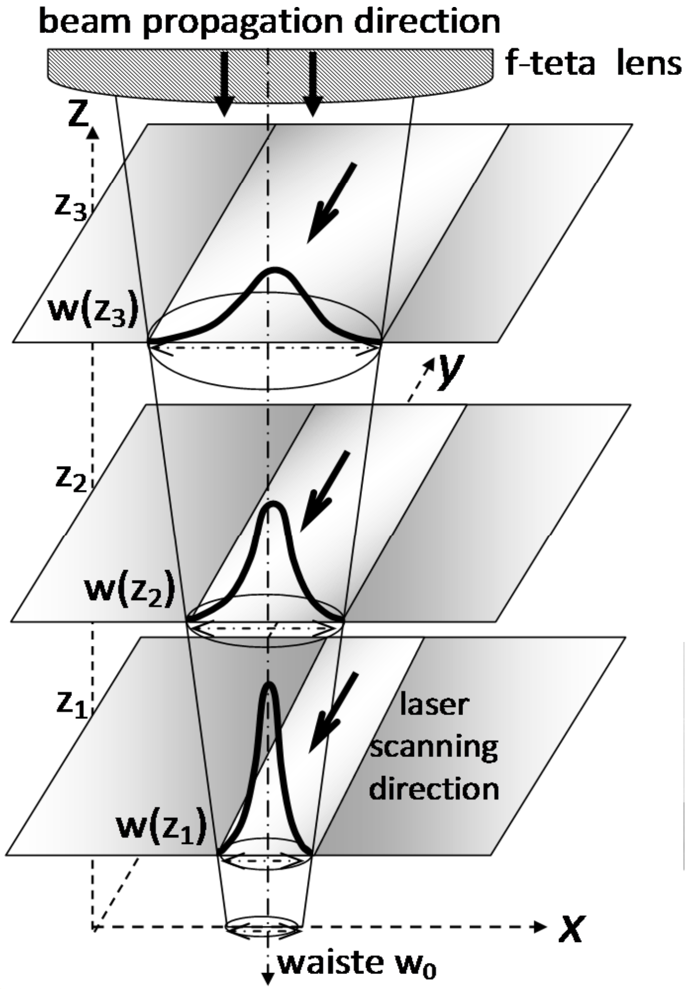
Laser sintering of TiO2 layer



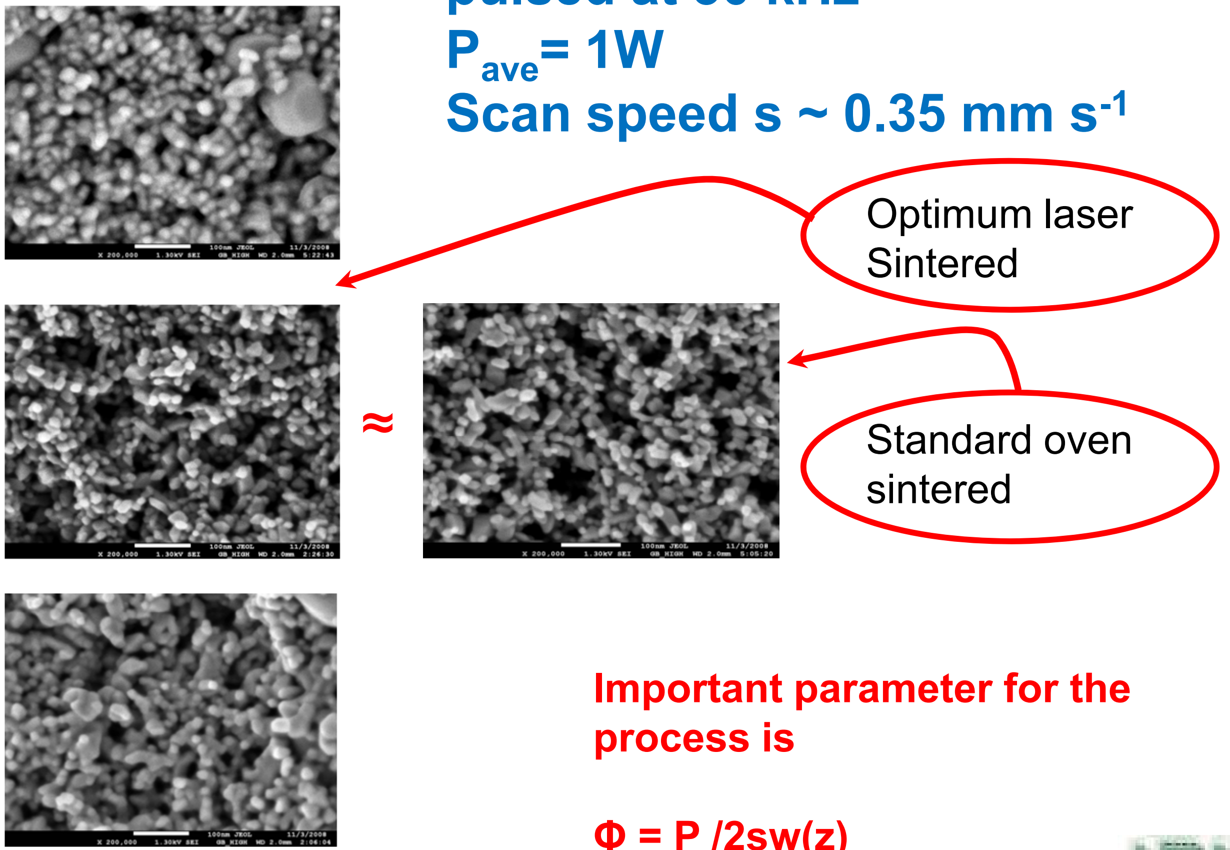


TiO2 laser sintering/1

Widely used in the thin film solar cell industry, laser scanning processing could bring about many advantages to DSC industrial production .
(non-contact, local, rapid, selective, scalable processing, low temperature)



U.V. laser (λ=355nm)
pulsed at 30 kHz
P_{ave}= 1W
Scan speed s ~ 0.35 mm s^{-1}



Important parameter for the process is

$\Phi = P/2sw(z)$

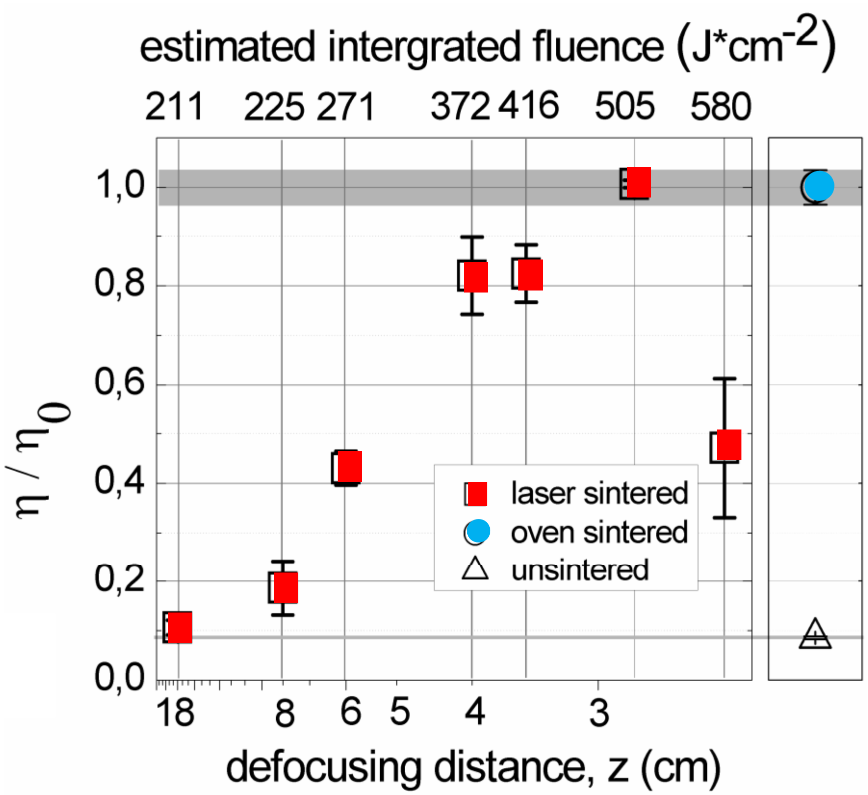
laser integrated fluence [J

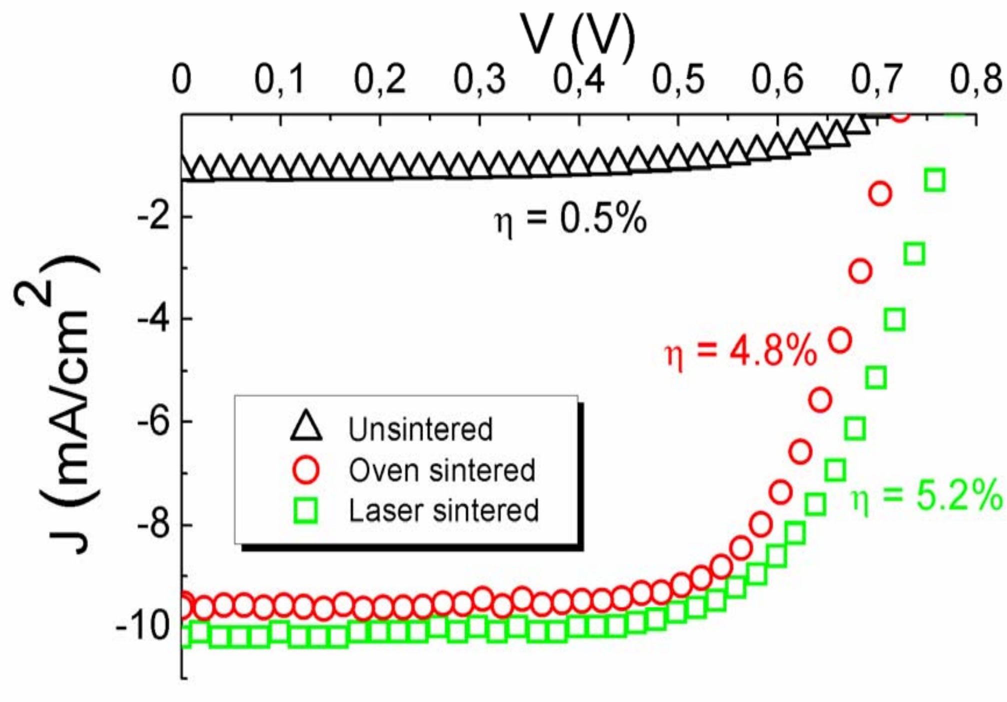
CHOSE

A. Di Carlo

TiO2 laser sintering/2

Clear trend of power conversion efficiency η vs. Φ



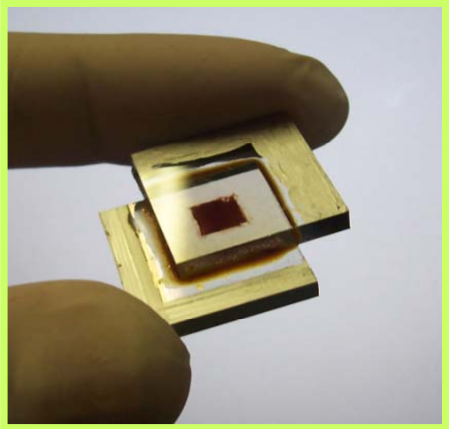


Record performance of DSCs with laser sintered TiO2

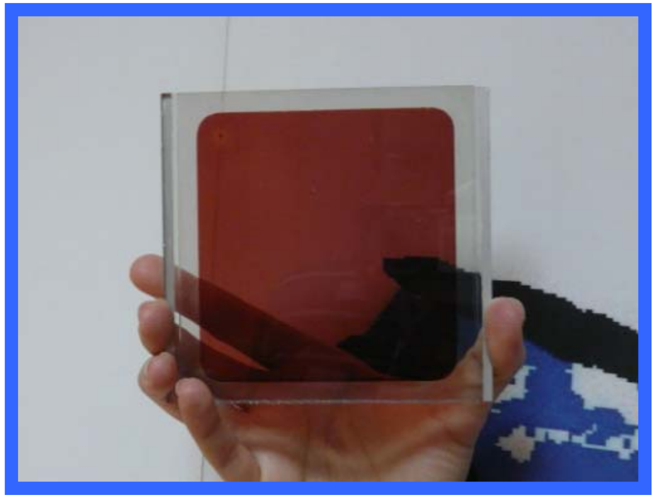
G.Mincuzzi, L.Vesce, A. Reale, A. Di Carlo, T.M. Brown, "**Laser Sintered Nanocrystalline Titanium Dioxide Films for Efficient Dye Solar Cell Device Fabrication**", APL 2009

From cells to modules
Large Area

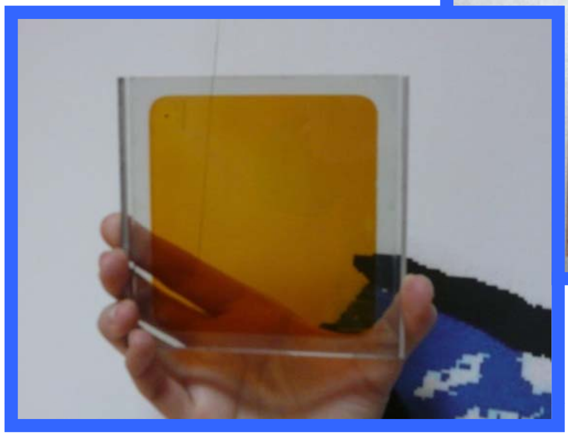
From small cell to (sub)module



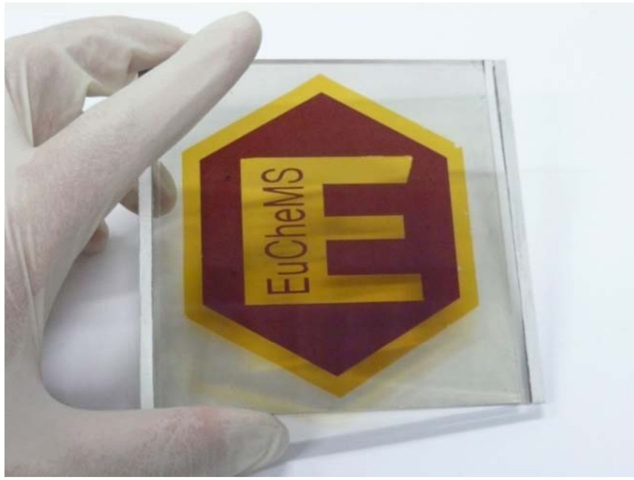
The easiest
(and wrong) way:
simple scale up



Cell scaling up and colours

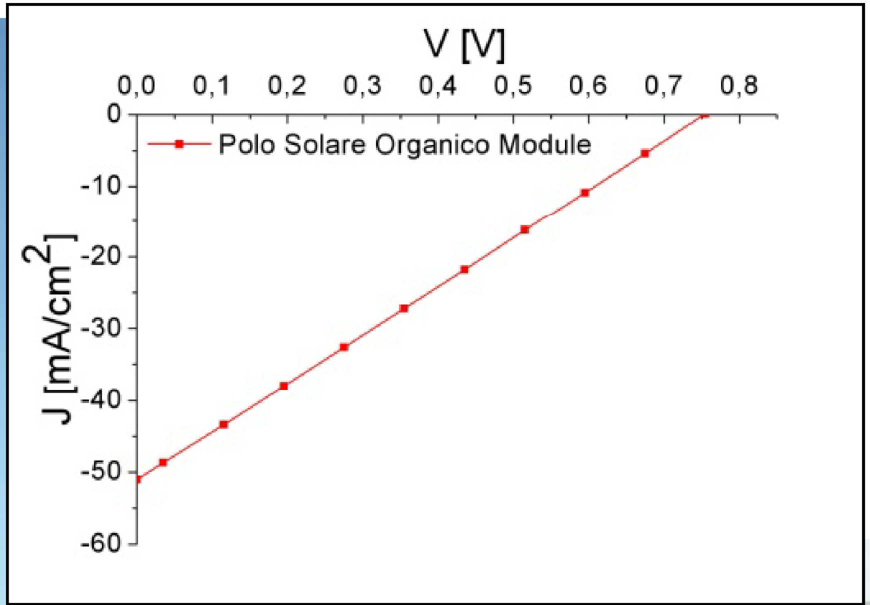


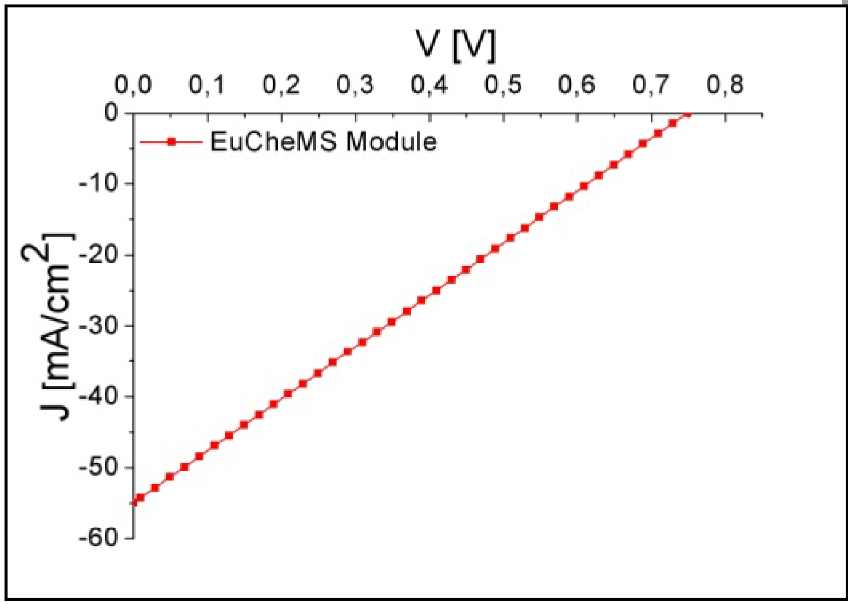
Cells with pattern



Cells with pattern

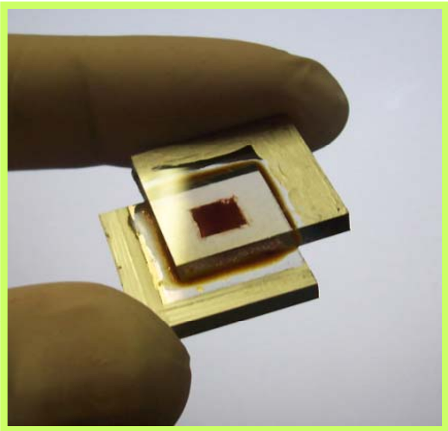
Example of patterned DSC (sigle cells)



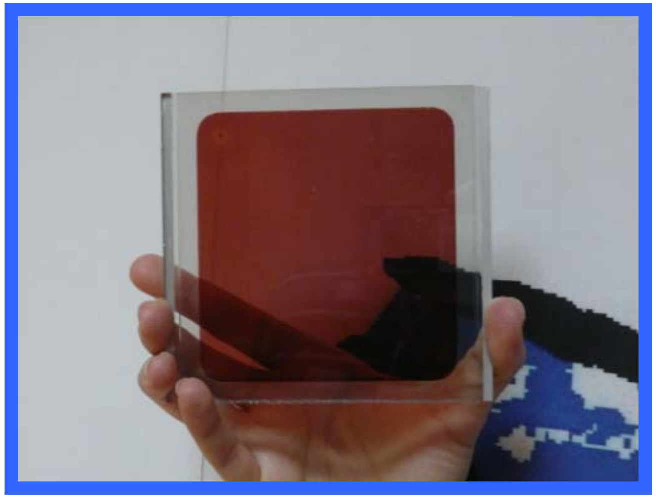


Very Very low efficiency

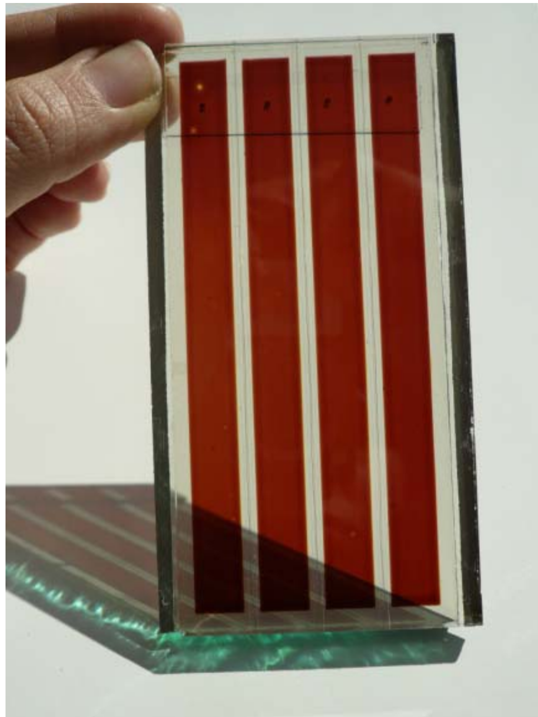
From small cell to (sub)module



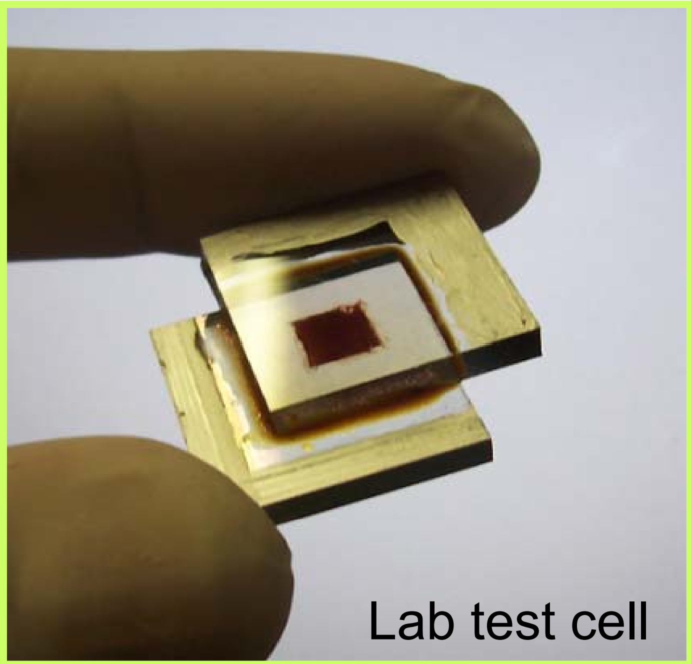
The easiest and wrong way: simple scale up

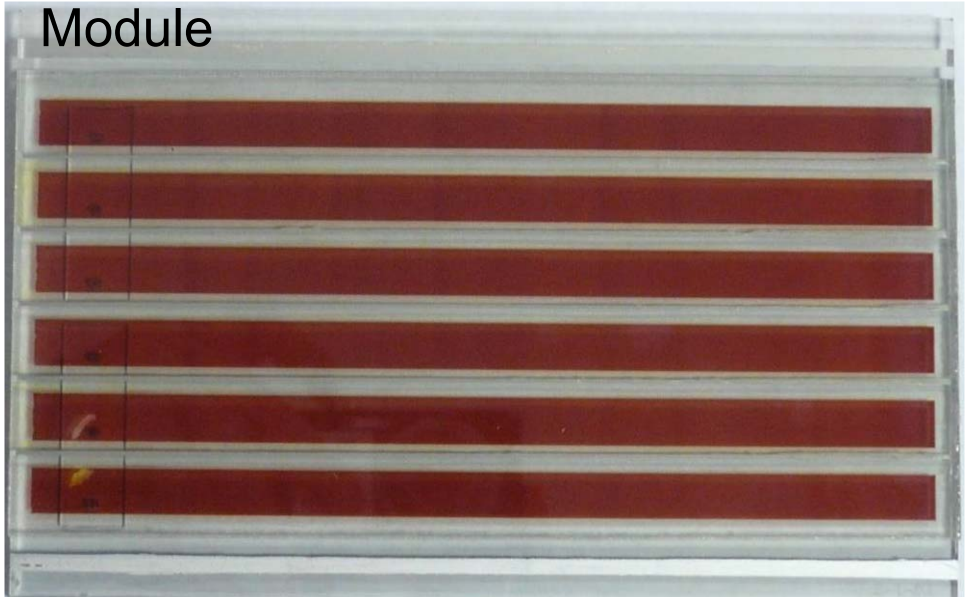


The right way: proper aspect ratio



Cells and modules





- Optimization of the materials
- Optimization of the deposition
- Optimization of sealing

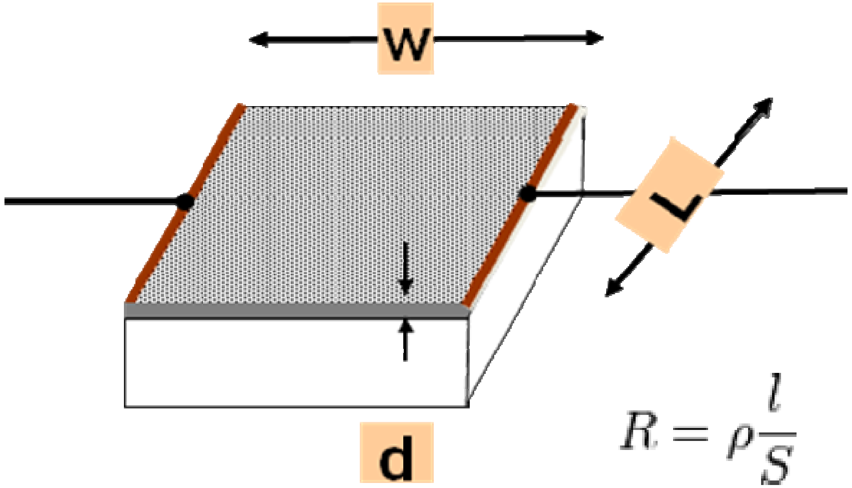
Scaling up is not trivial and it is one of the major problem !

Cell optimization +

-inteconnections
- reduction of series resistance
- balance among cells
- engineering of the module design
- thermal expansion

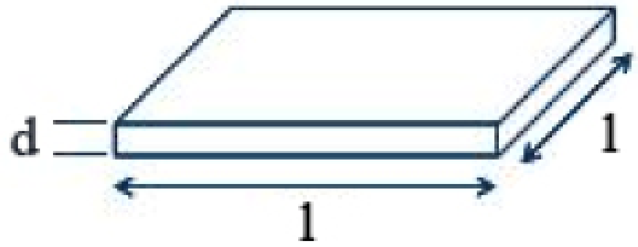
Large area cells: The sheet resistance

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



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

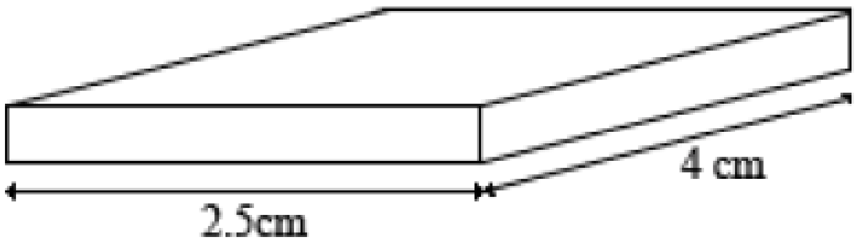
If
L=W



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

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

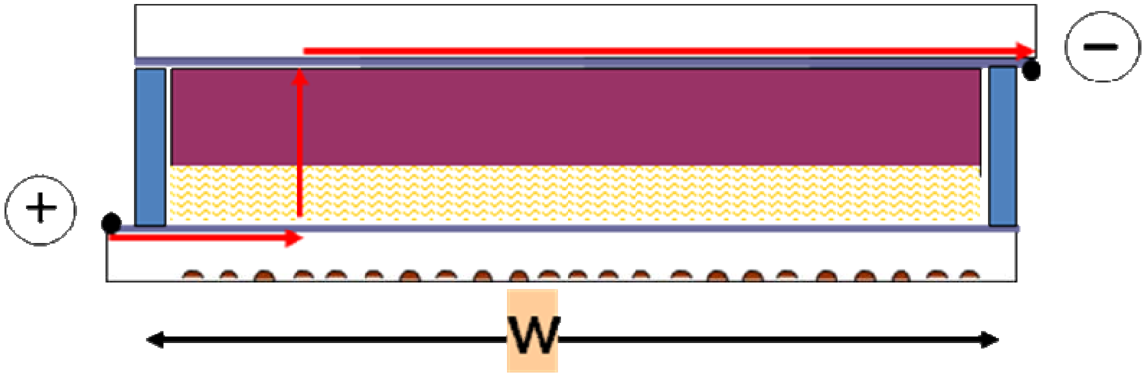
Example



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

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

Sheet resistance influence



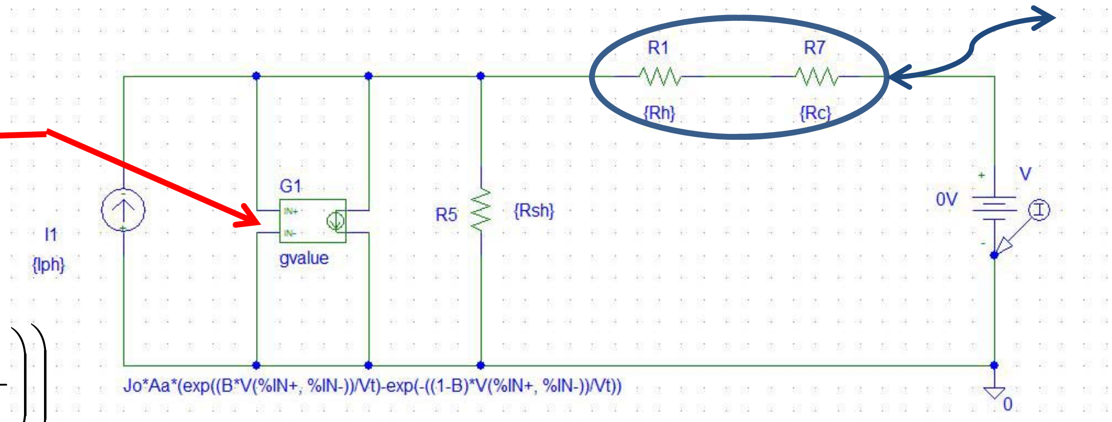
$$\Delta V = RI = \left[\frac{\rho W}{dL}\right]\left[J \cdot L \cdot W\right] = J \cdot W^2 \cdot R_{square}$$

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

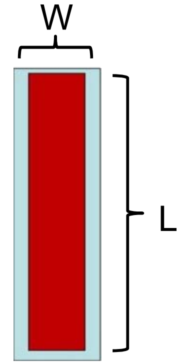
1) Small area cell (0.5cm x 0.5 cm) = ΔV=0.02V
2) Large area cell (10 cm x 10 cm) => ΔV = 8 V >> V_{oc} !!

Single Cell - simulated data

Non Linear Resistance
Butler-Volmer eq.



$$Rs = \frac{\rho}{d}\frac{W}{L}$$



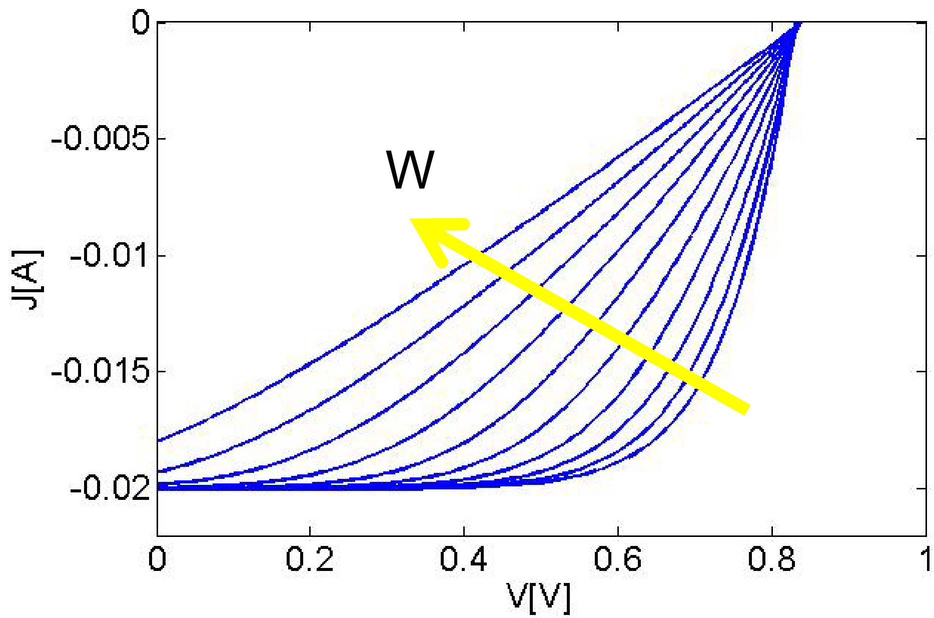
$$J = J_0\left(\exp\left(\beta\frac{V}{V_T}\right) - \exp\left(-(1-\beta)\frac{V}{V_T}\right)\right)$$

$\beta = 0.35$ $J_0 = 7.5\times10^{-7}$ A $V_T = 26$ mV @ RT

$\frac{\rho}{d} = TCO$ sheet resistance $= 8\Omega/\square$

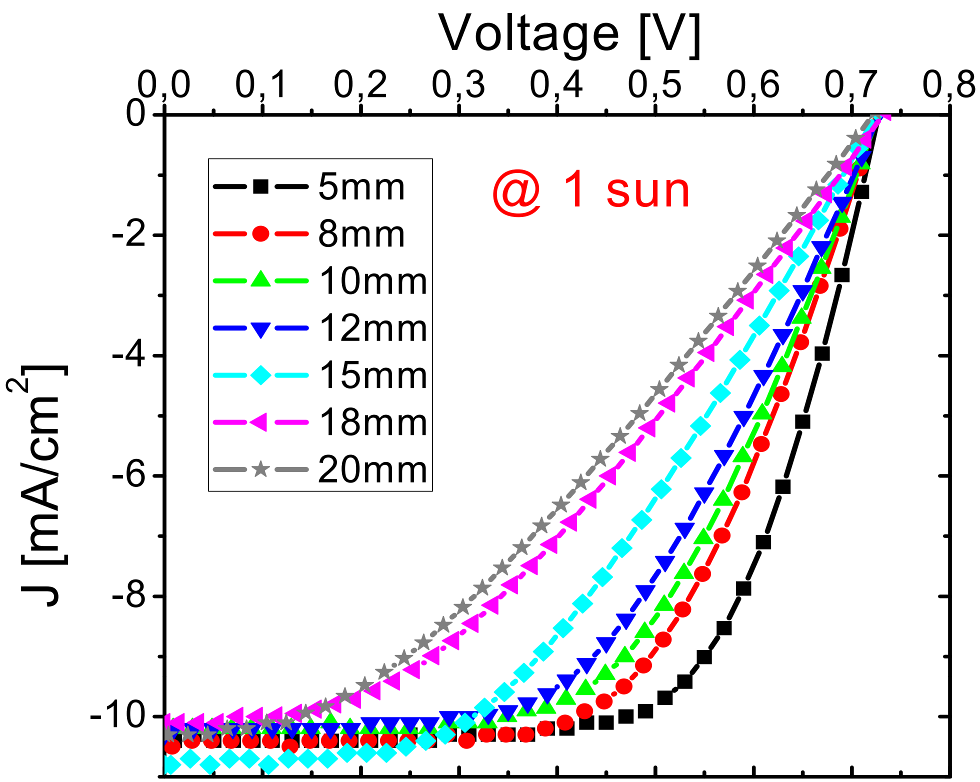
L= 5 cm; W=1.5mm

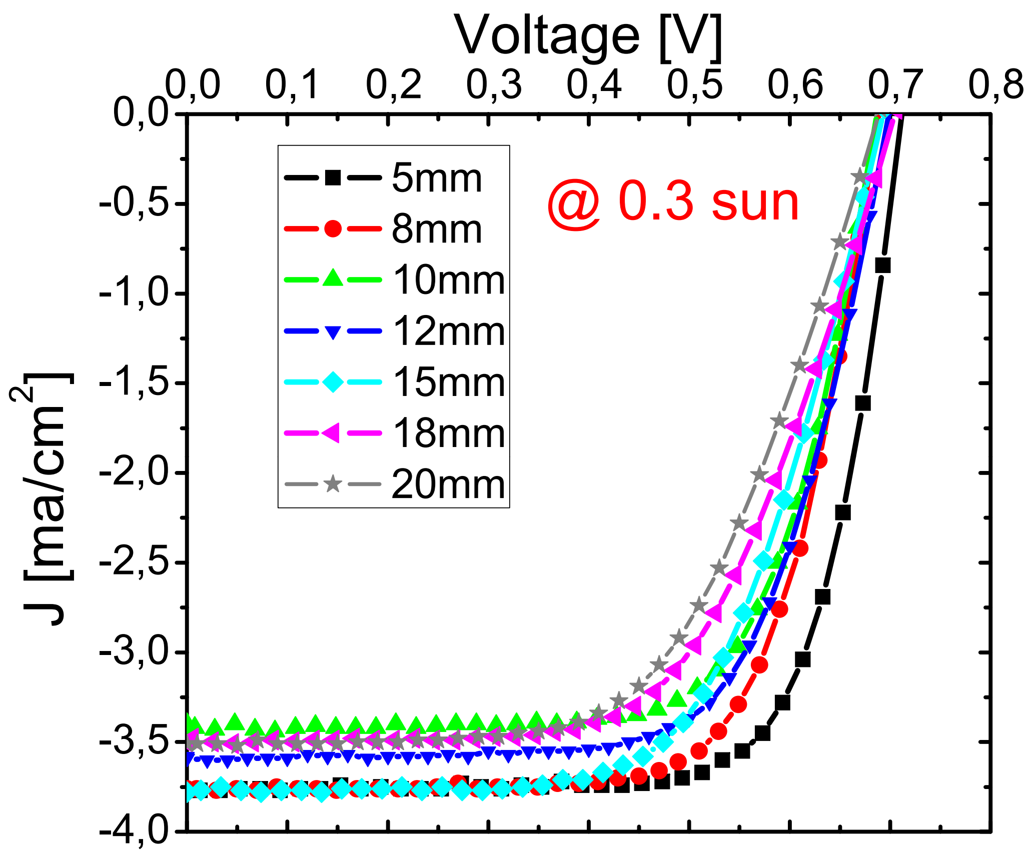
W(mm)	Rs(Ω)	FF	eff
2	0.8	68.9	11.5
4	1.1	66.2	11.1
6	1.4	62.5	10.4
8	1.7	57.7	9.6
10	2.1	52.1	8.7
12	2.4	46.1	7.7
14	2.7	40	6.7



Single Cell - experimental data

F. Giordano et al, HOPV conference 2009

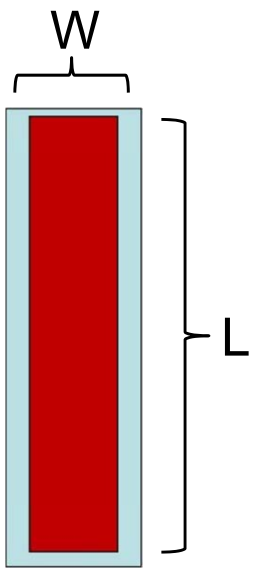


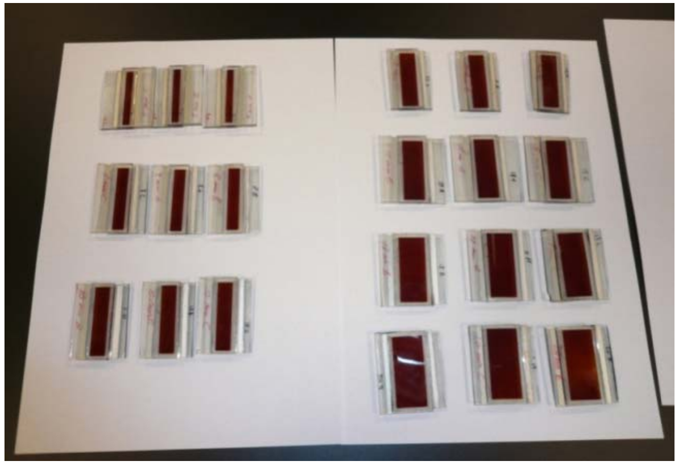


At 0.3 Sun the current is smaller with respect to 1 Sun and consequently ΔV is smaller.

Single Cell - experimental data

F. Giordano et al, HOPV conference 2009





1 set of cells L = 44mm,

W= 5, 8, 10, 12, 15, 18, 20 mm

Single titania layer of 6 microns

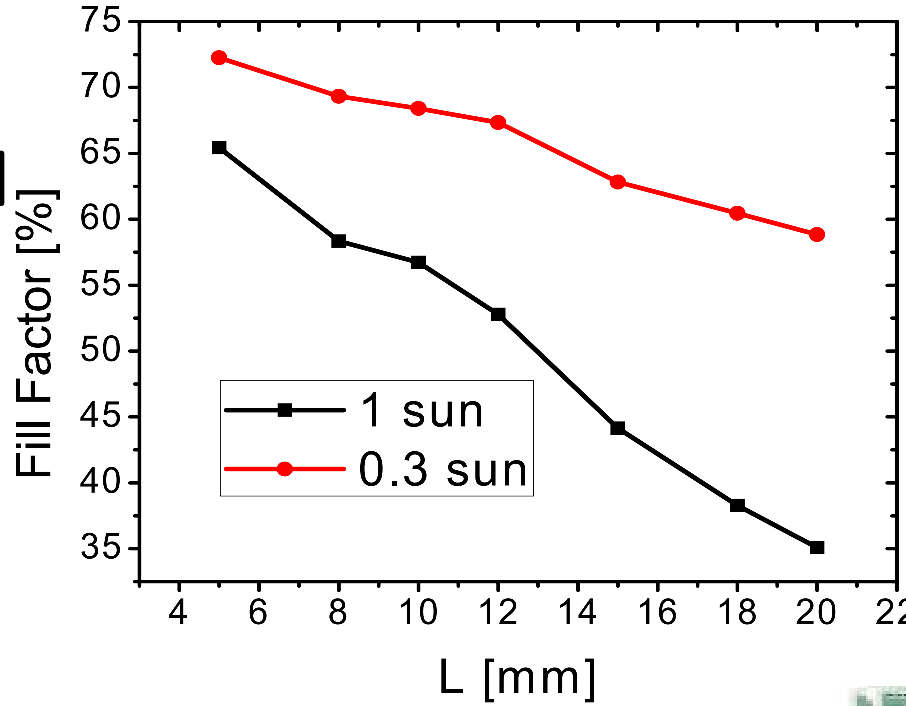
Jsc=10 mA/cm^2 Voc=730 mV

starting efficiency = 4.7%

(W=5 mm, total area 2.2cm^2)

$$\frac{\rho}{d} = TCO \text{ sheet resistance} = 8\Omega/\square$$

$$Rs = \frac{\rho}{d}\frac{W}{L}$$

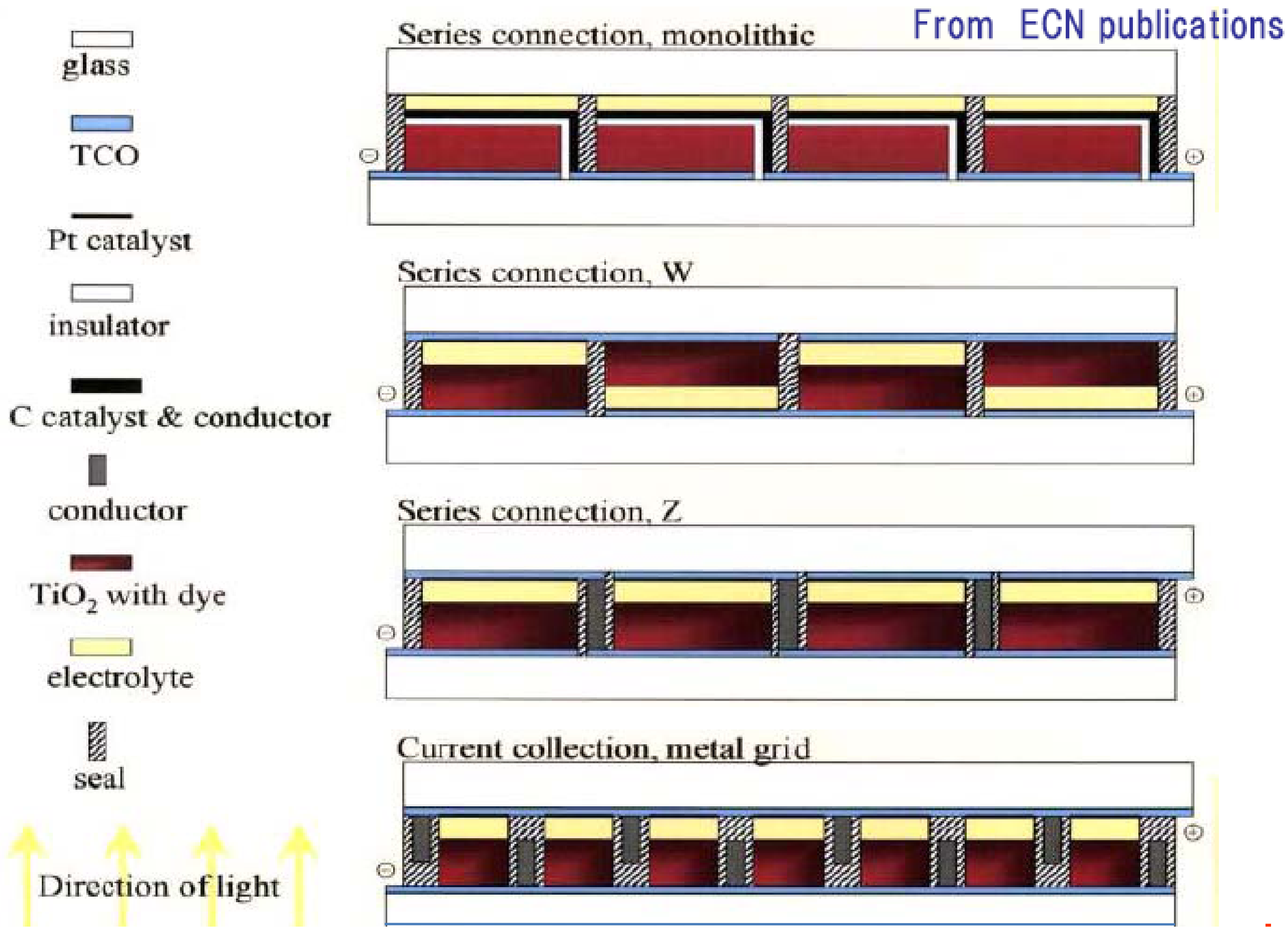


From large area cells to (sub)module

Well …and now …

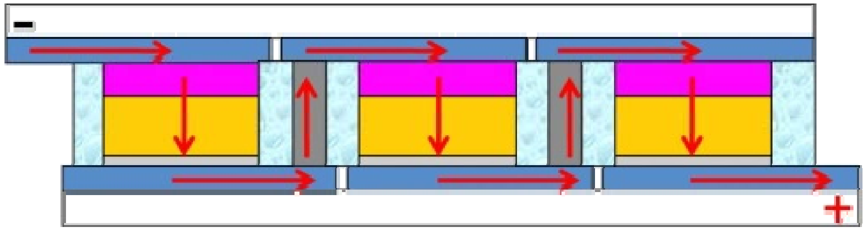
How can we realize a large area module with a certain open circuit voltage and a certain short circuit current ?

There are several ways to do it.


From ECN publications
glass
TCO
Pt catalyst
insulator
C catalyst & conductor
conductor
TiO_2 with dye
electrolyte
seal
Direction of light
Series connection, monolithic
Series connection, W
Series connection, Z
Current collection, metal grid

W and Z schemes

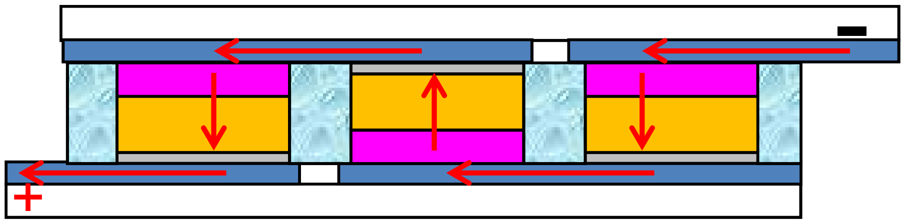
✓Optimized and separated processes for WE and CE substrates



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

Z

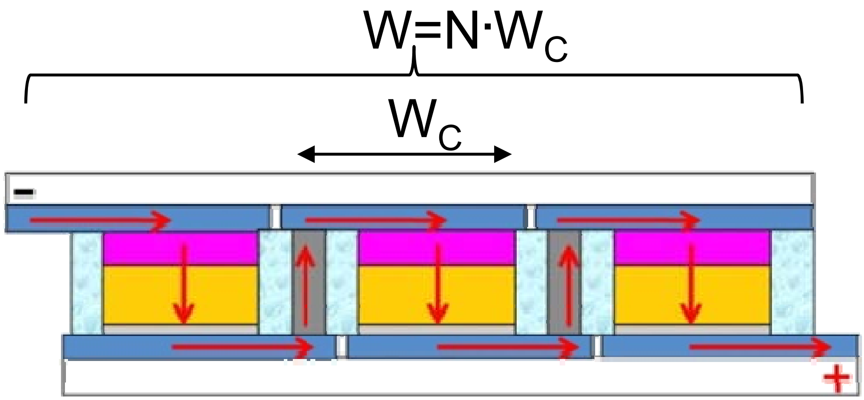
✓No vertical connections
✓High AR



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

W

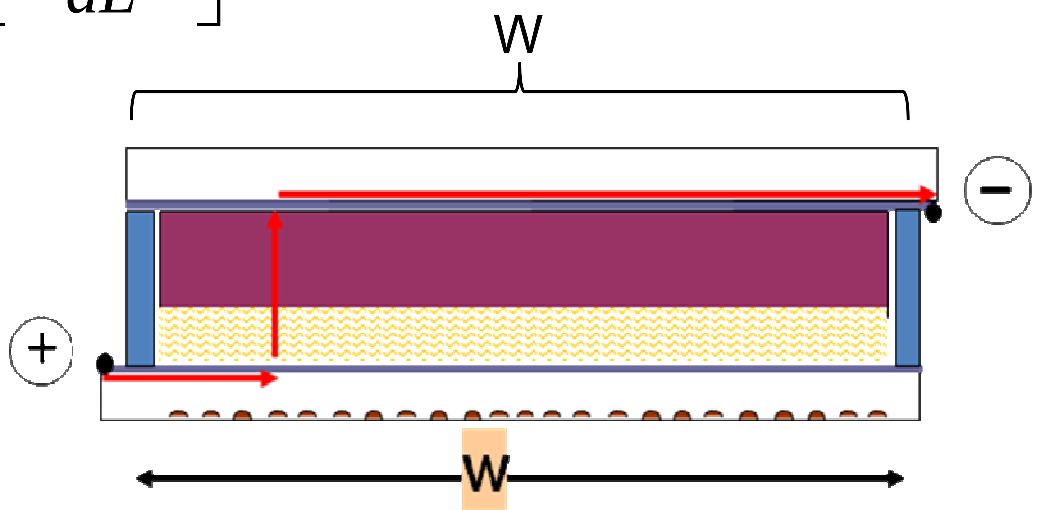
Module with N cells connected in series



$R_{interconnects} = 0$

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

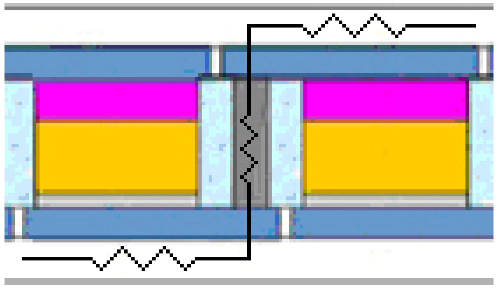
Large area cell

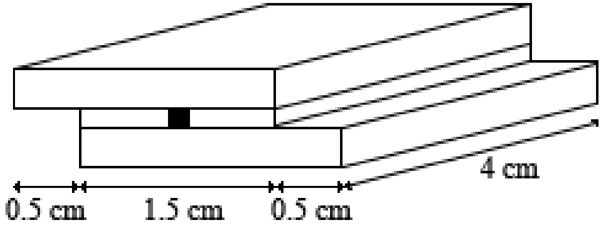


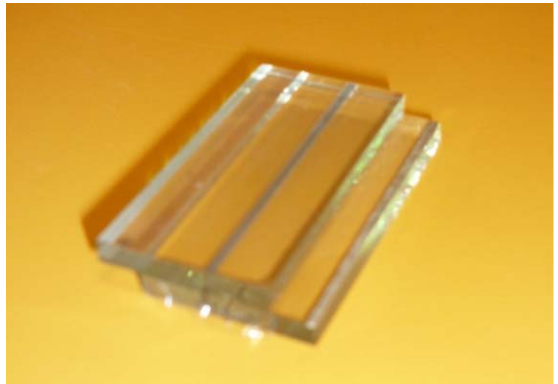
$$\Delta V_M = \frac{\Delta V_{LargeCell}}{N}$$

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

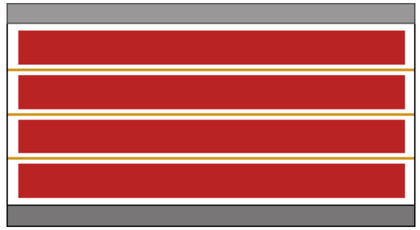
Z scheme - Vertical interconnections

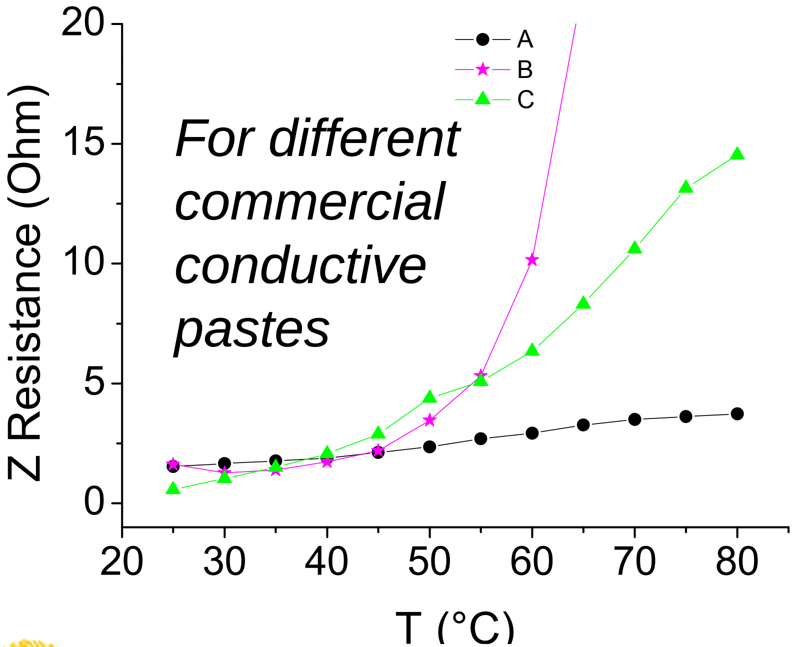




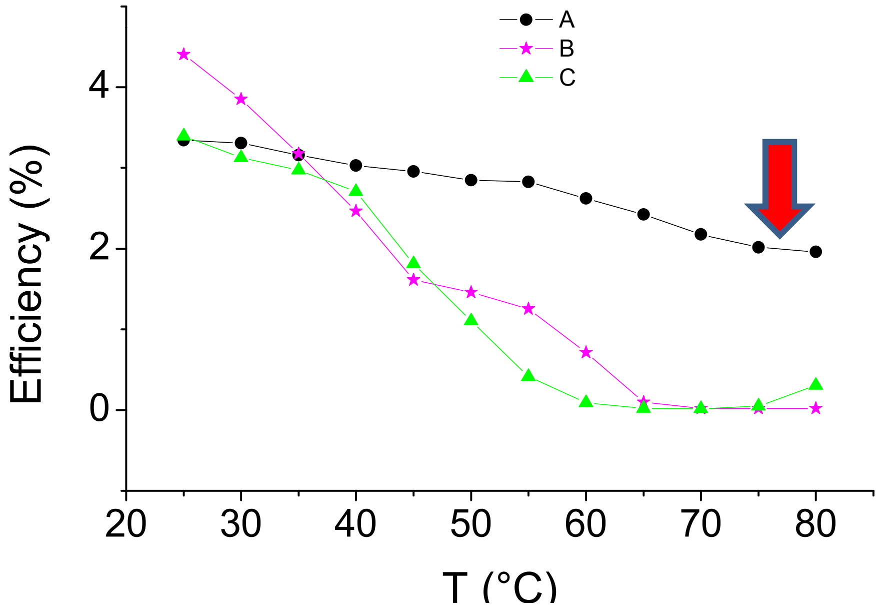


Mismacth in thermal expansion coefficient between sealing and interconnection affect s the value of electrical resistance

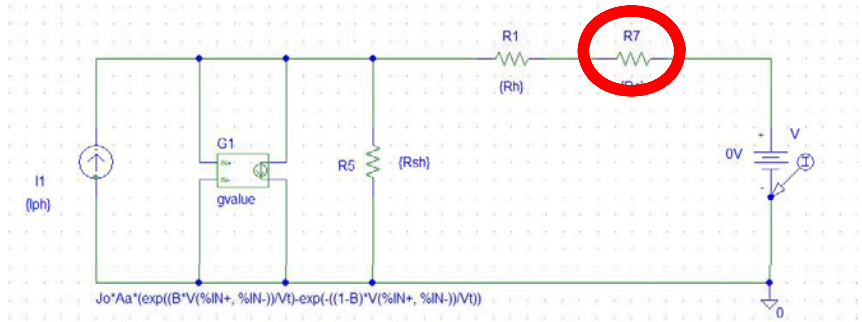




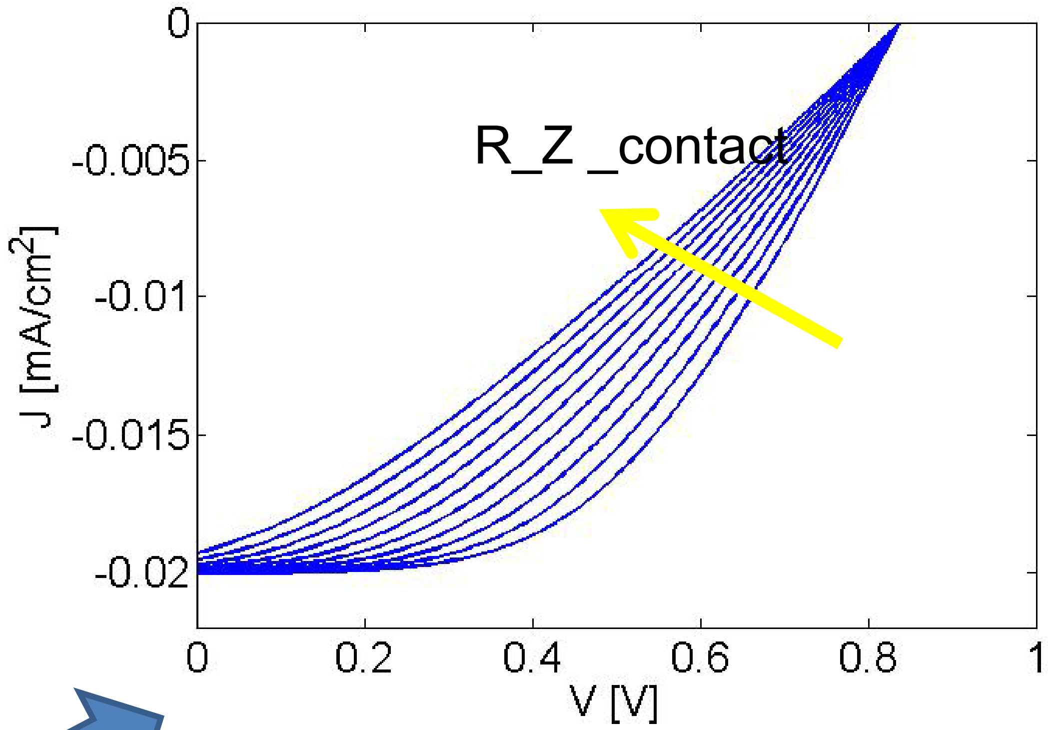
module



Vertical interconnections- simulated data



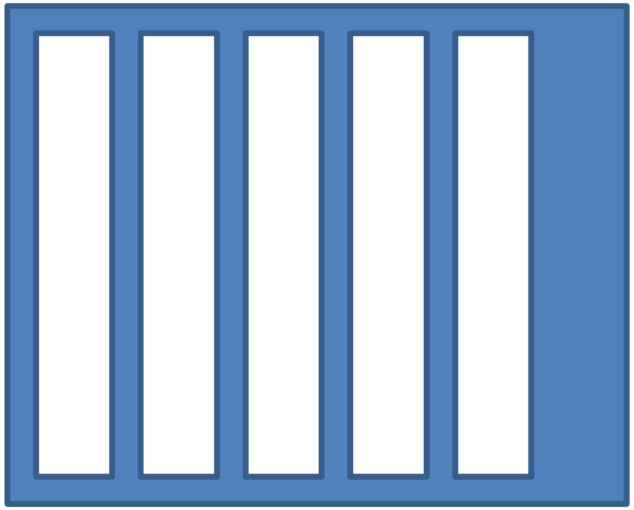
R_interdistance+R Z contact

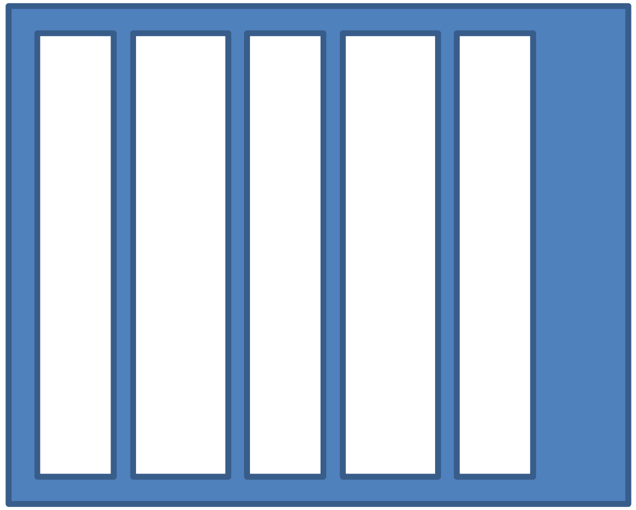


Z(Ω)	Rs(Ω)	FF	eff
0.4	2.5	49	8.2
0.8	2.9	46.1	7.7
1.2	3.3	43.3	7.3
1.6	3.7	40.7	6.8
2.0	4.1	38.3	6.4
2.4	4.5	36.1	6.1
2.8	4.9	34.1	5.7

Z and W projected layout

Z

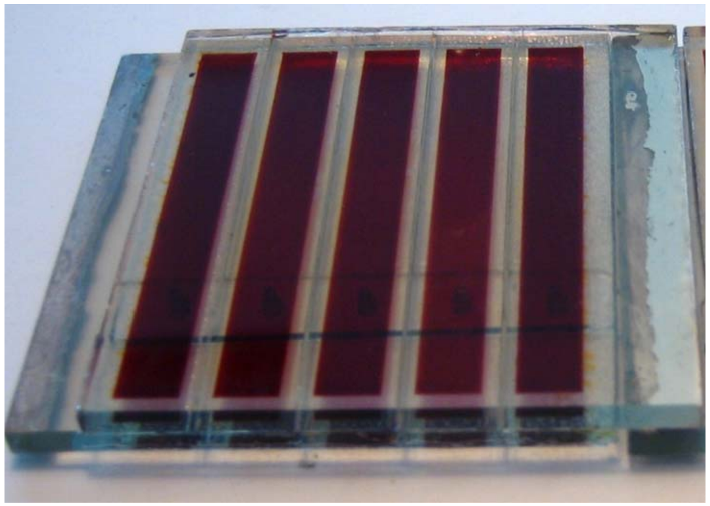


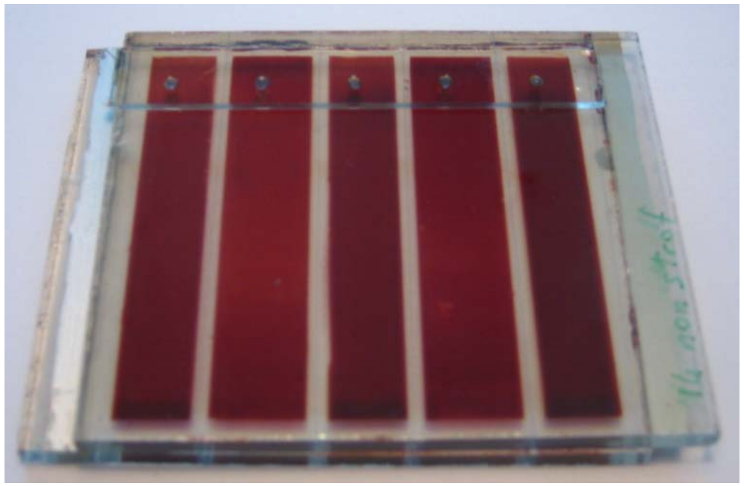


W

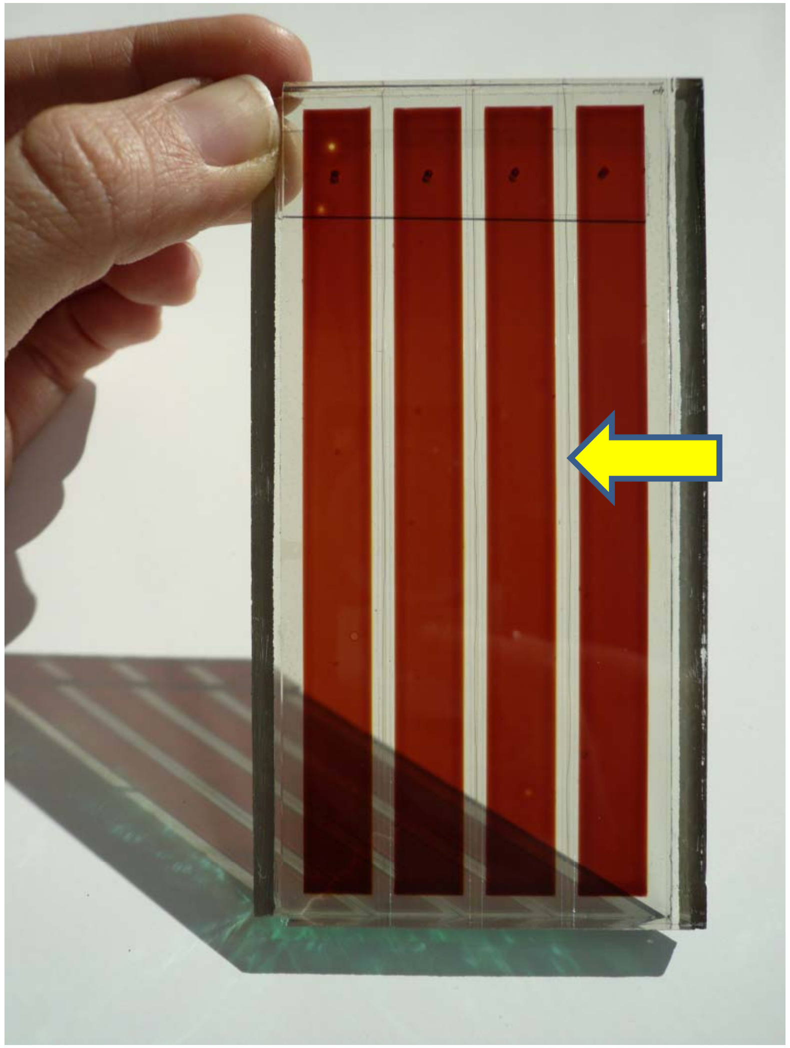
L= 8 mm d=3
Vertical connection Paste A

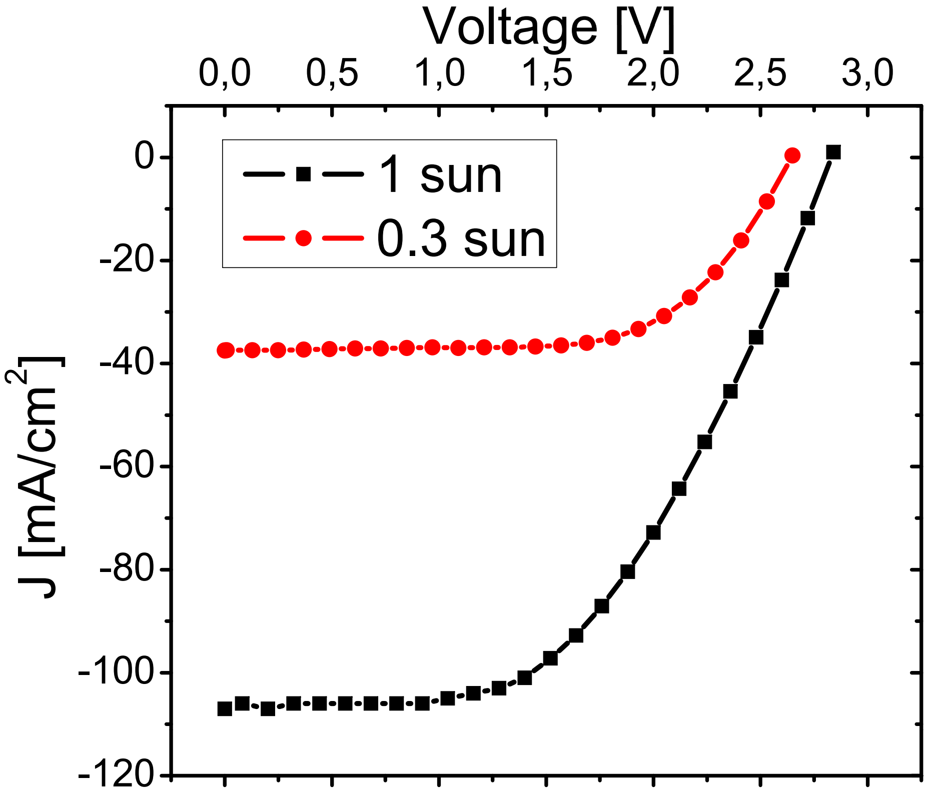
L_1= 8mm L_2= 10 mm d=2
Electrolyte B





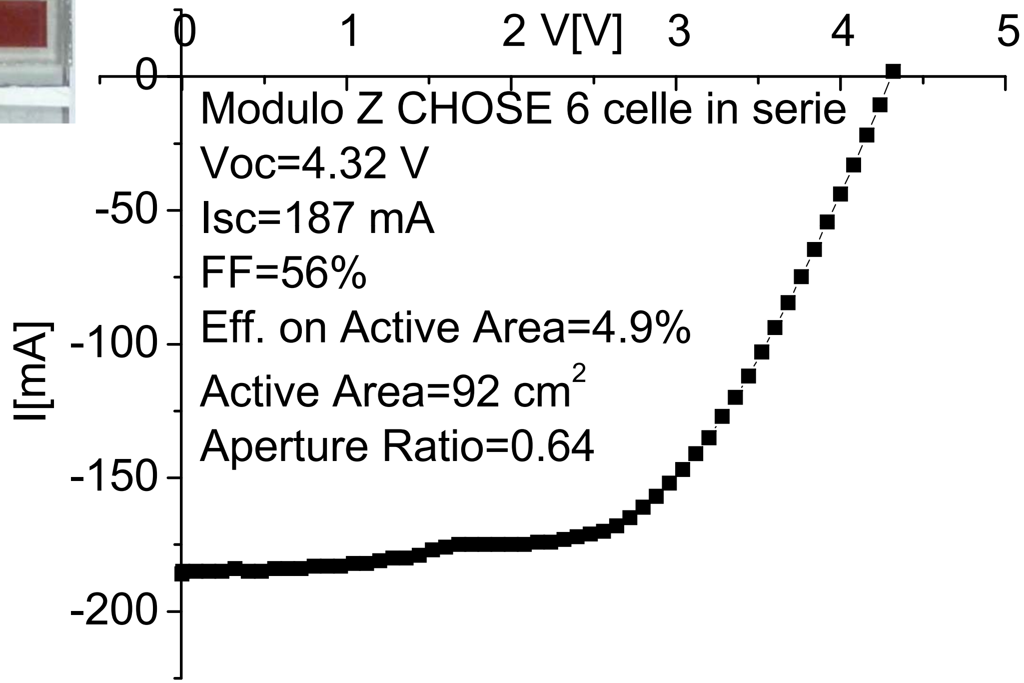
Z-module – micrometer interconnections





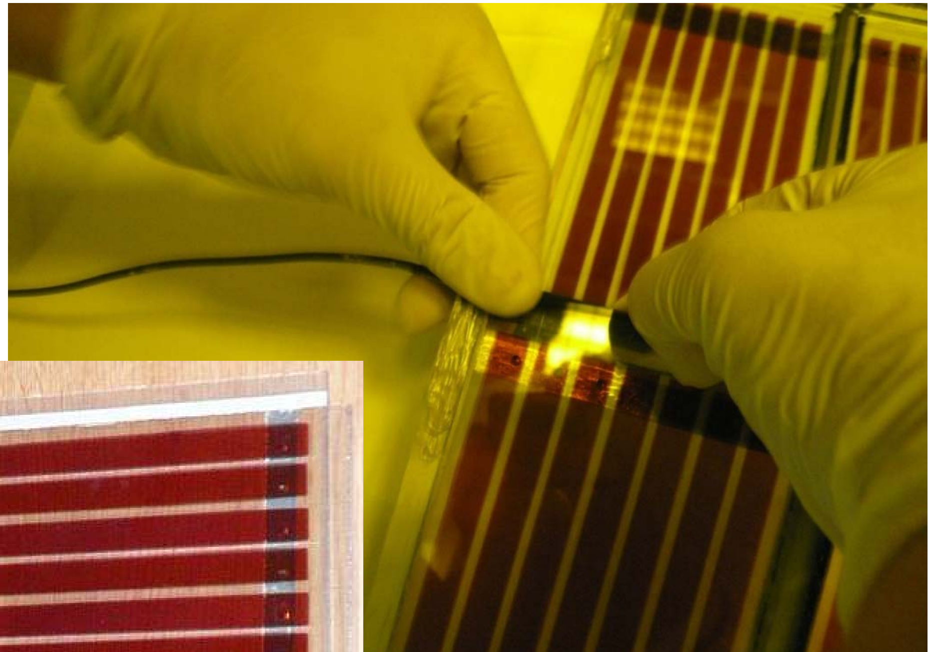
	1 sun	0.3 sun
Isc [mA/cm²]	1.06E-1	3.77E-2
Voc [V]	2.84	2.65
FF [%]	51.01	64.34
η [%]	4.15	5.8

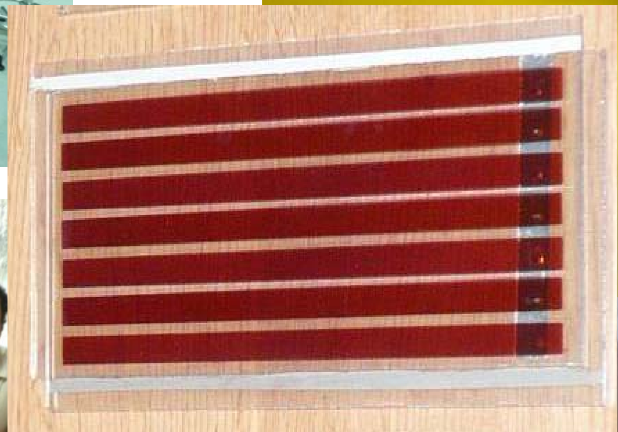
Z module 6 cells

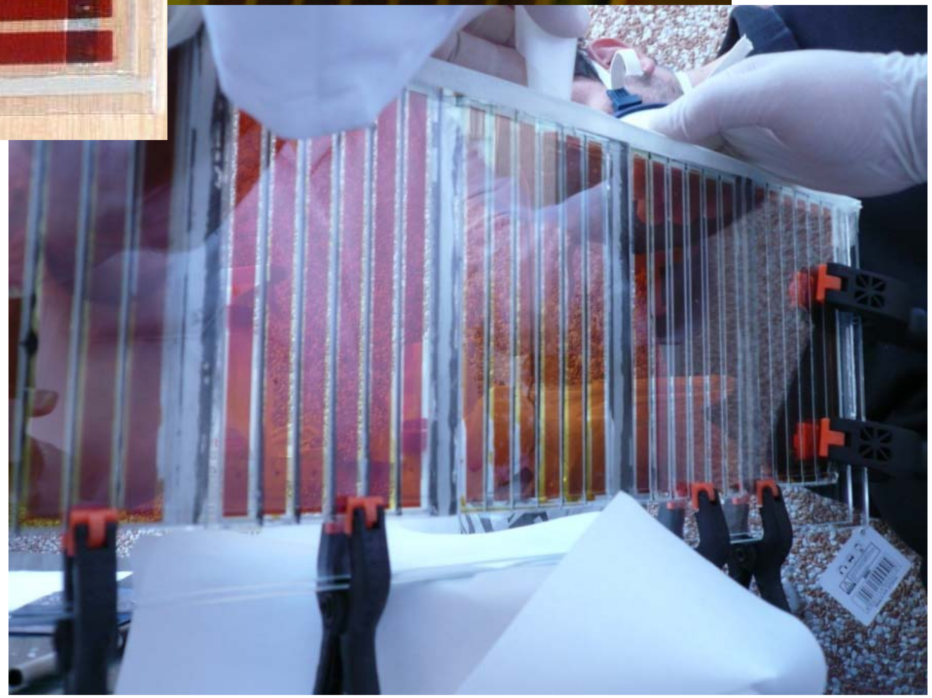


From Modules to Panels

Modules Assembly, bus bar connections

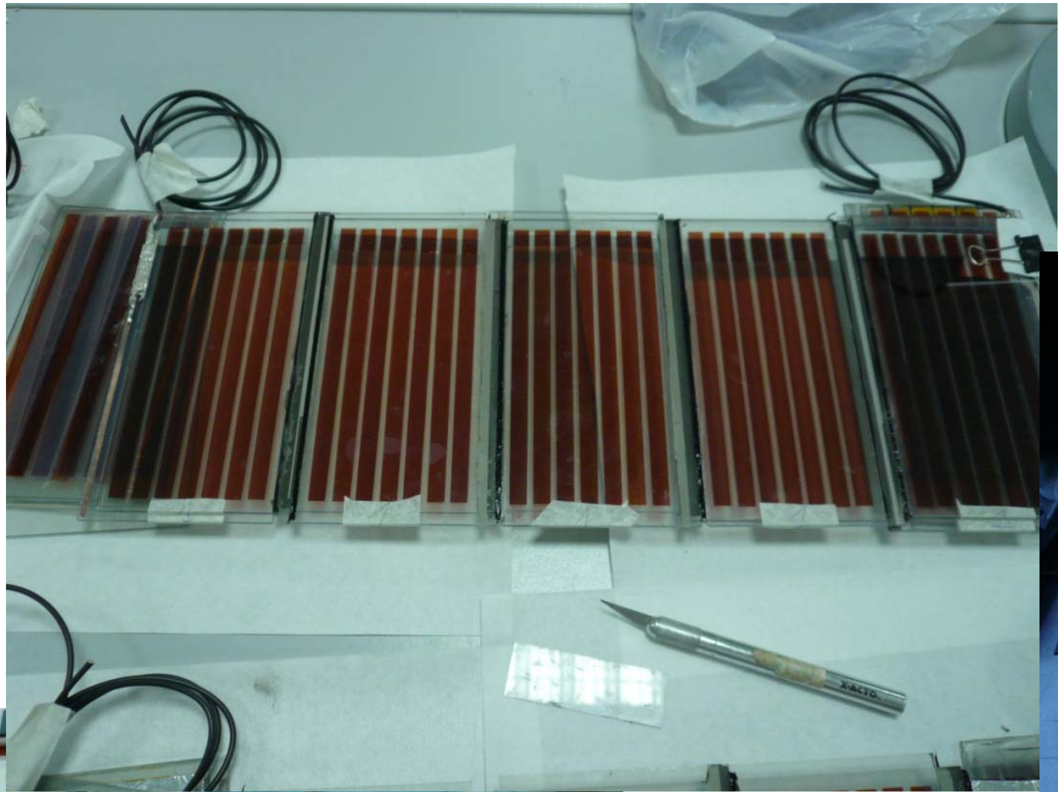


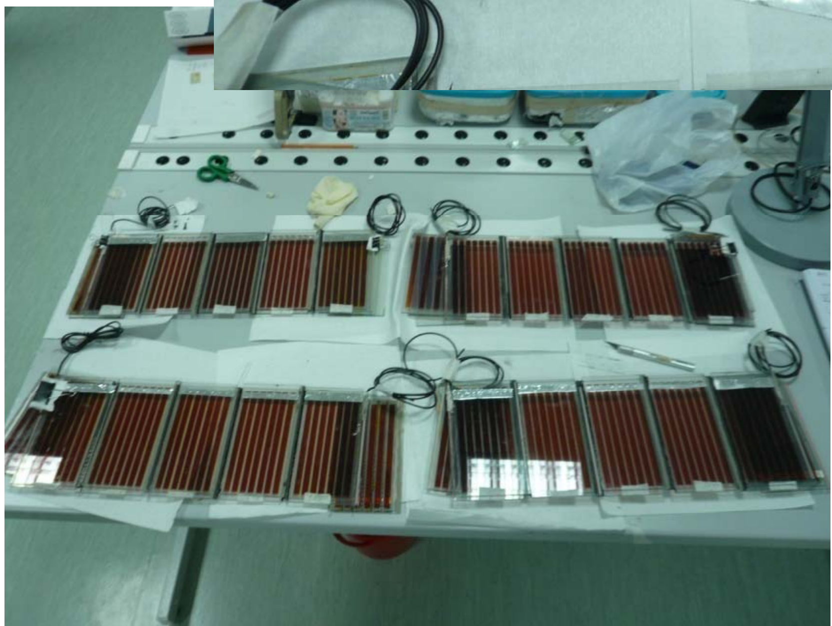


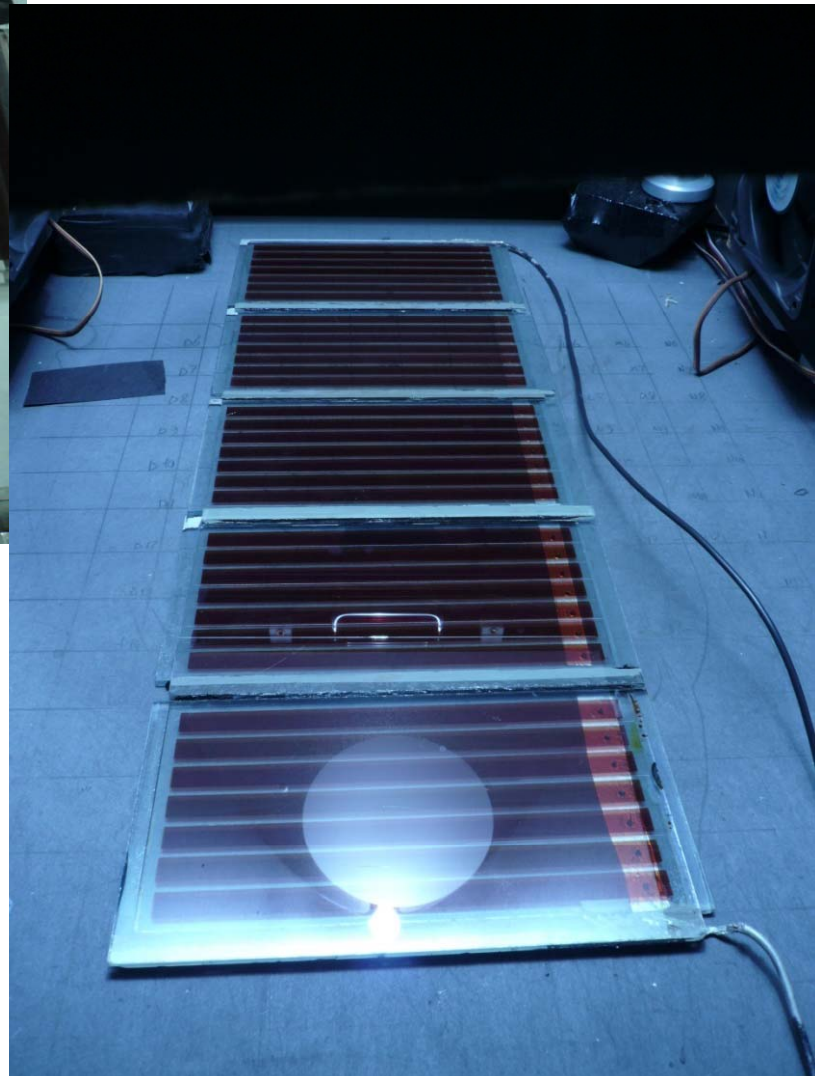


CHOSE

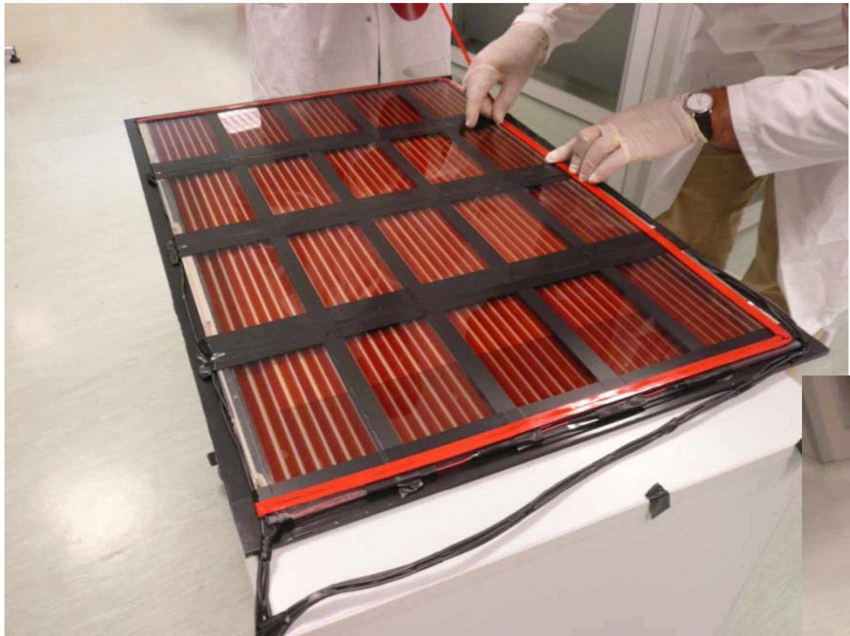
Strings

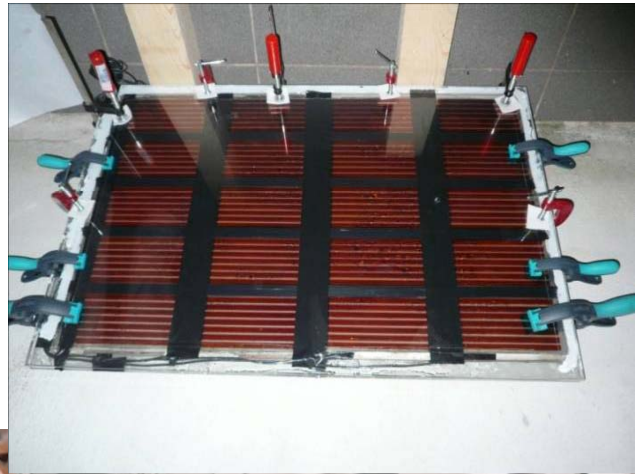


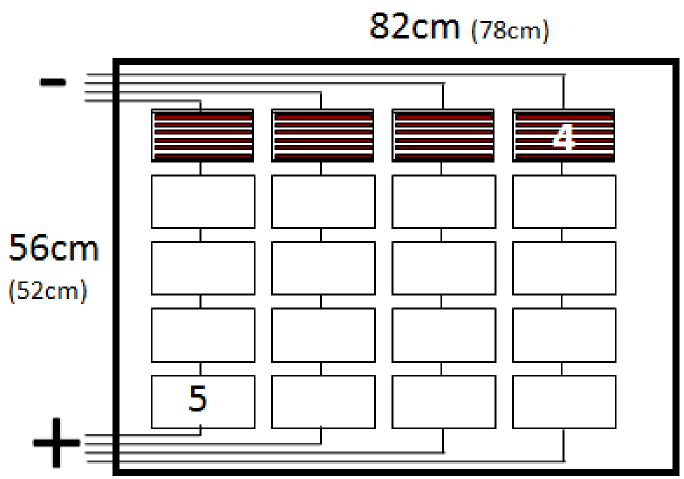


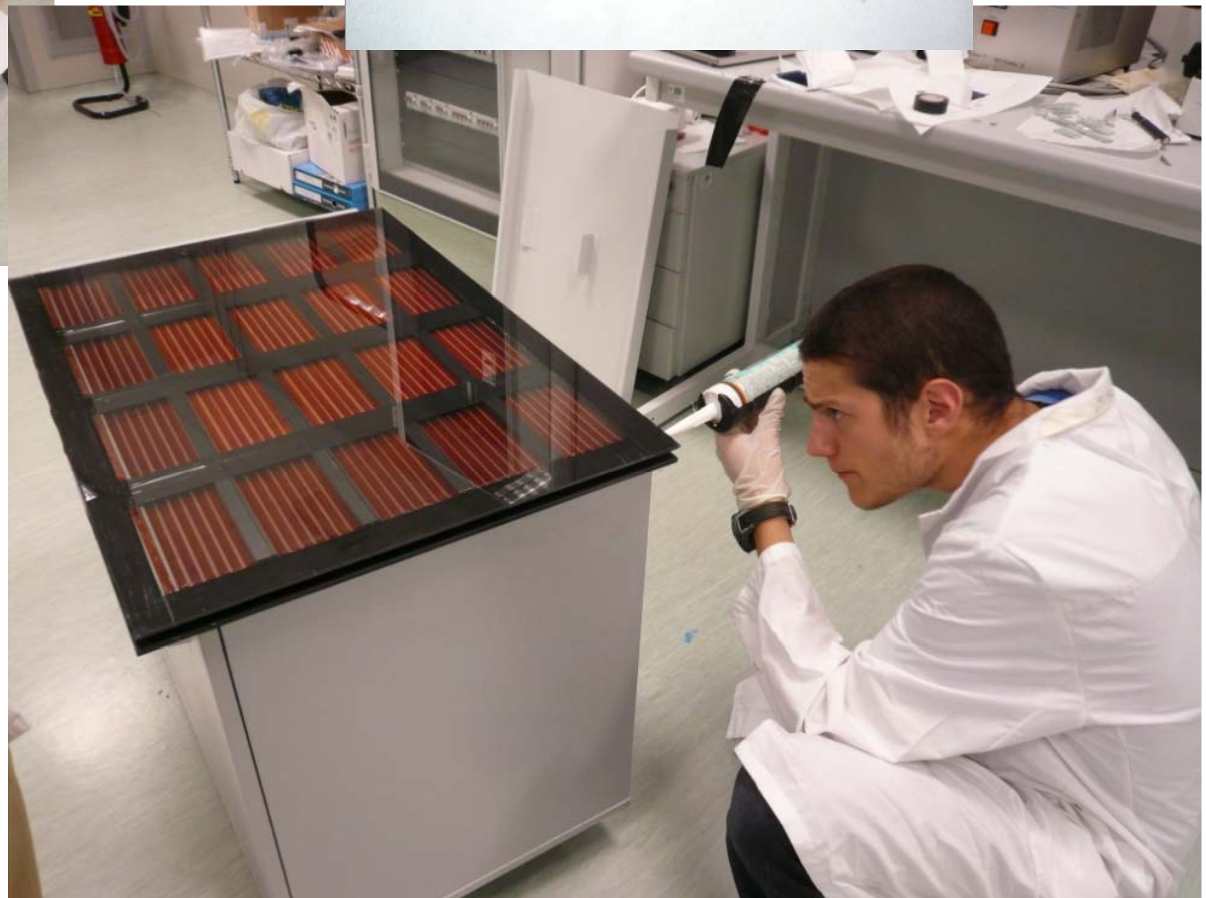


Panel assembly









Final panel

Fabrication

Automatic Screen-Printing (Baccini)

Batch fabrication facilities

a) Belt oven
b) Hole drilling machine
c) Dye Applicator

Batch fabrication facilities

a) Dye profiling
b) Electrolyte applicator
c) Sealing applicator

Pilot line

Toward Industrialization

Applications Dyesol

DSSC Façade System
at the CSIRO Energy Centre
Newcastle, Australia

Applications (AISIN-Toyota)

AISIN - Japan

Applications (Sony)

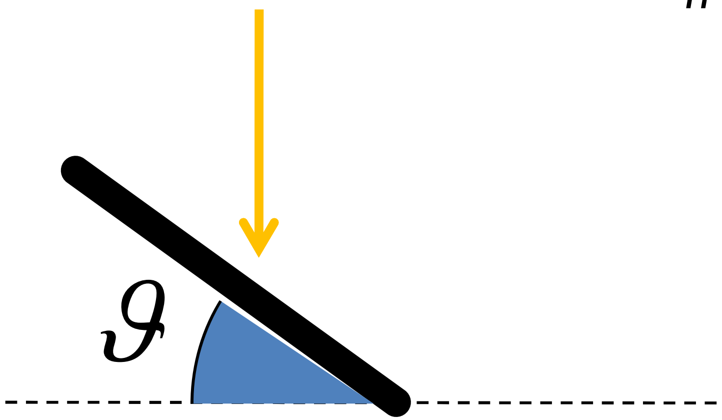
Outdoor measurements

ESTER
Energia Solare TEst e Ricerca
Laboratori di Fisica Tecnica Ambientale
Università degli Studi di Roma 'Tor Vergata'
Prof. Spena – Dr. Cornaro

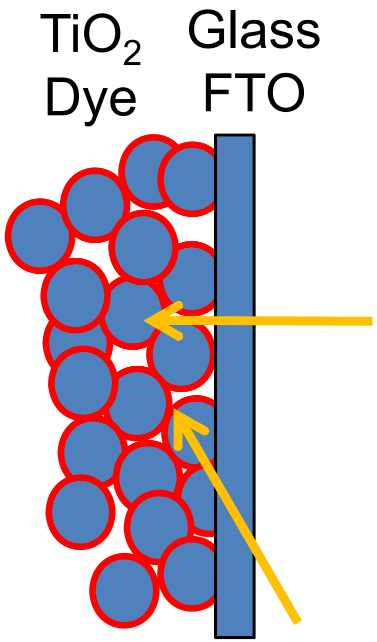
Outdoor PV Test and meteorological station

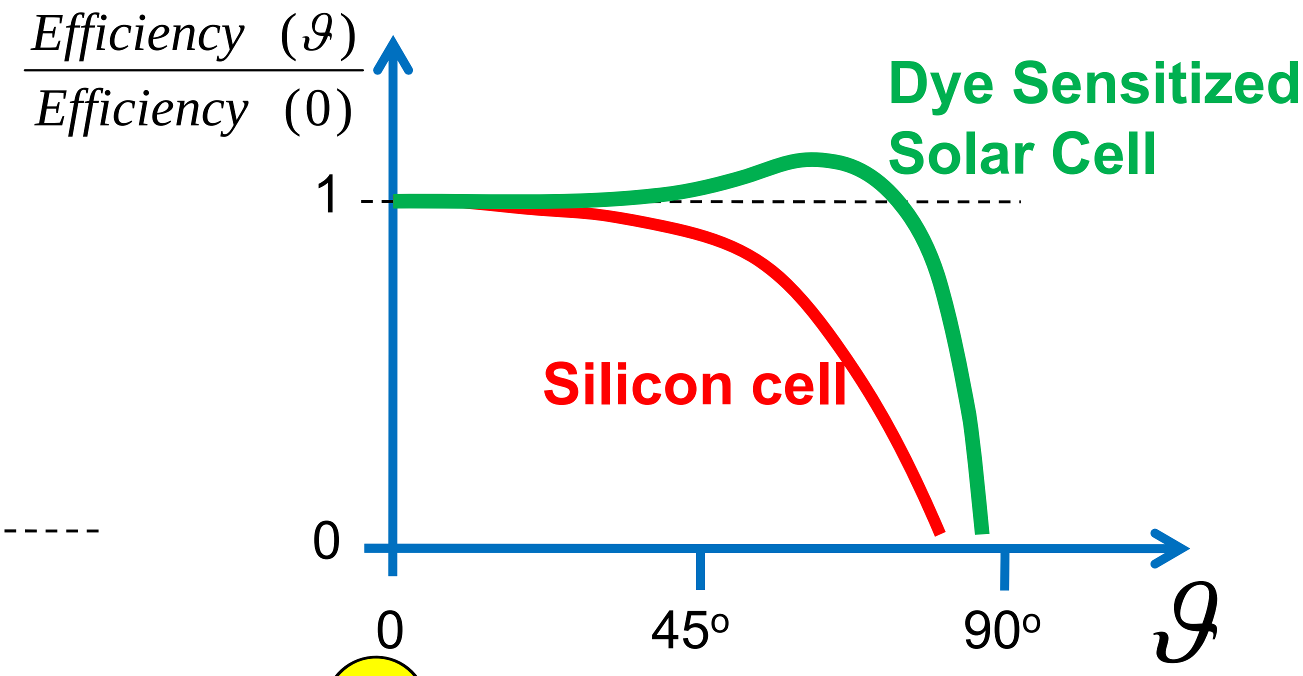
Main Characteristics:
- Meteorological station with also direct/indirect light intensity meas.
- up to 6 panel contemporary measurement with also DSC cell meas.
- 2 rotation axis
- Solar spectra measurement

Angular dependence



1



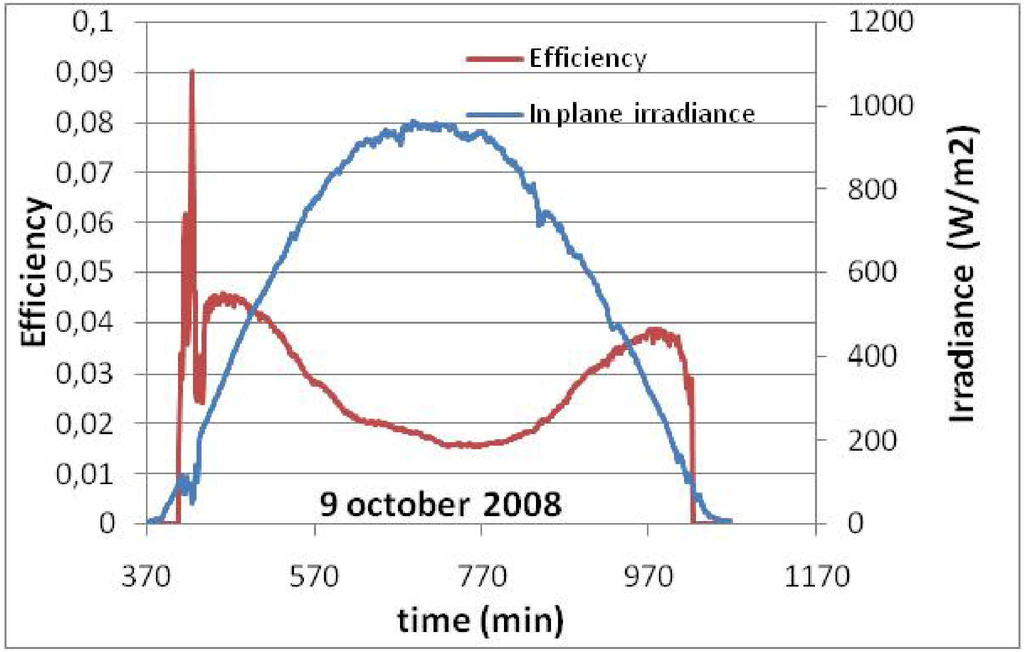


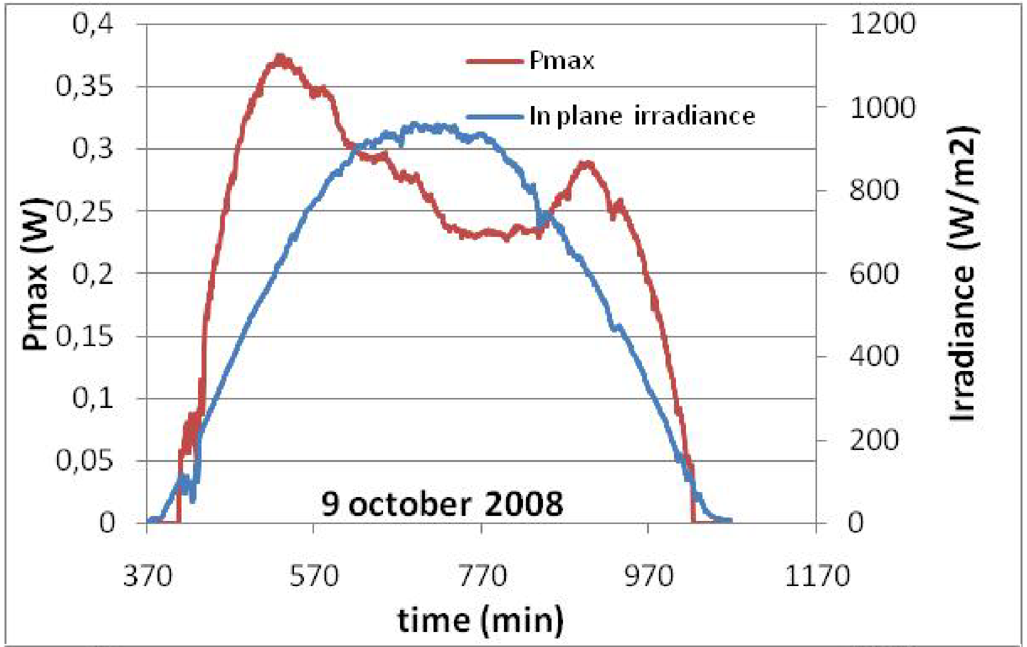
2

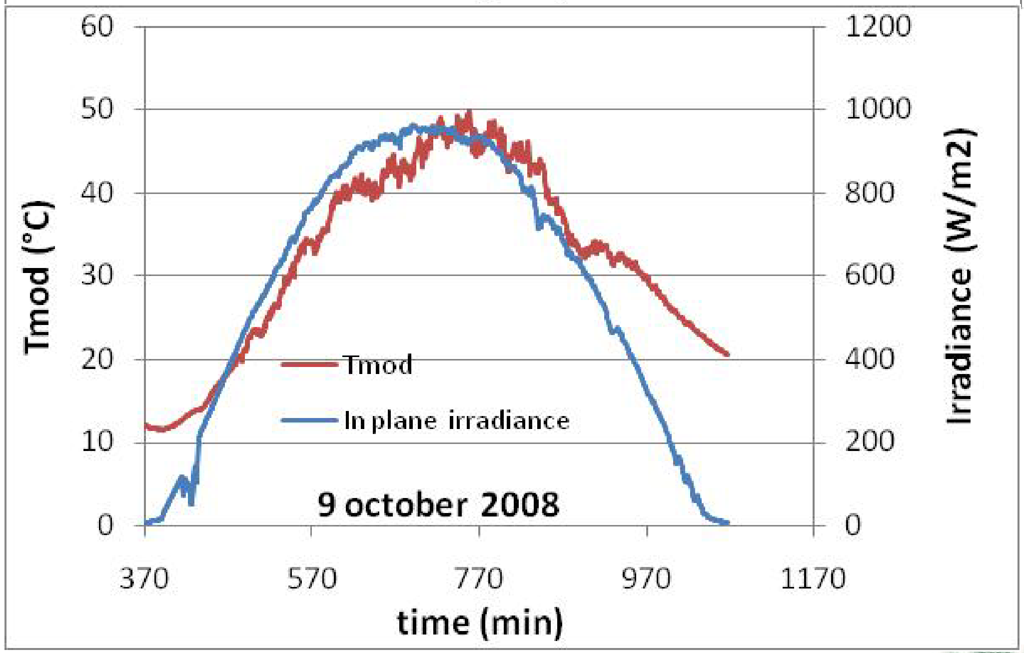
Lower is the light intensity higher is the efficiency of the electrolyte to sustain the generated carriers

Path length increases with increasing angle

Outdoor Module test – Clear day

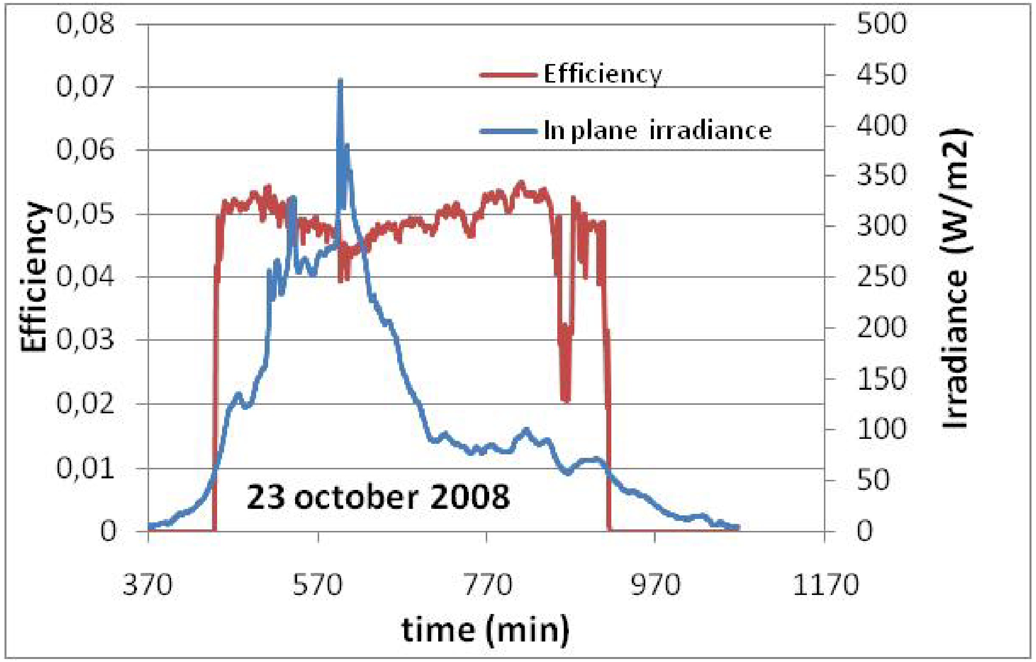


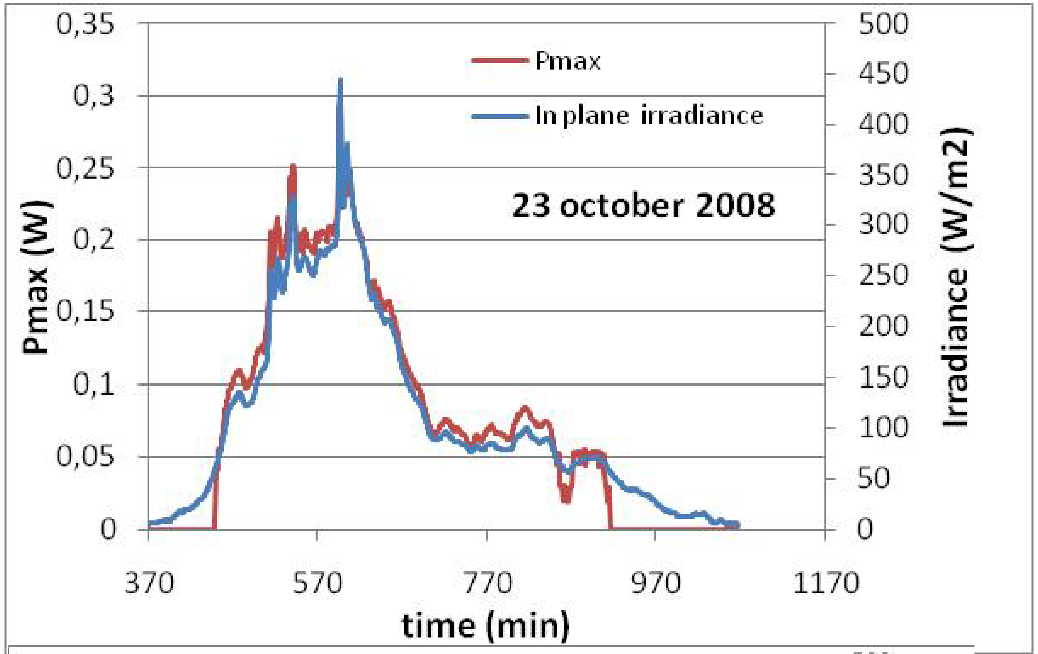




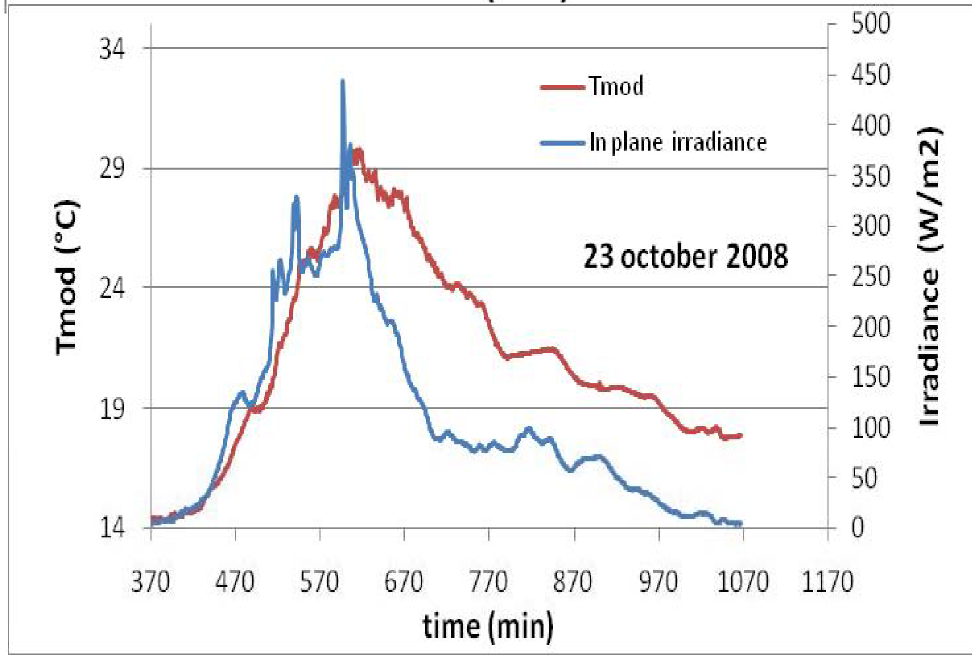
Light is mainly direct

Outdoor Module test – Cloudy day





Light is mainly diffused



Energy production

[T. Toyoda et al. / Journal of Photochemistry and Photobiology A: Chemistry 164 (2004) 203–207]

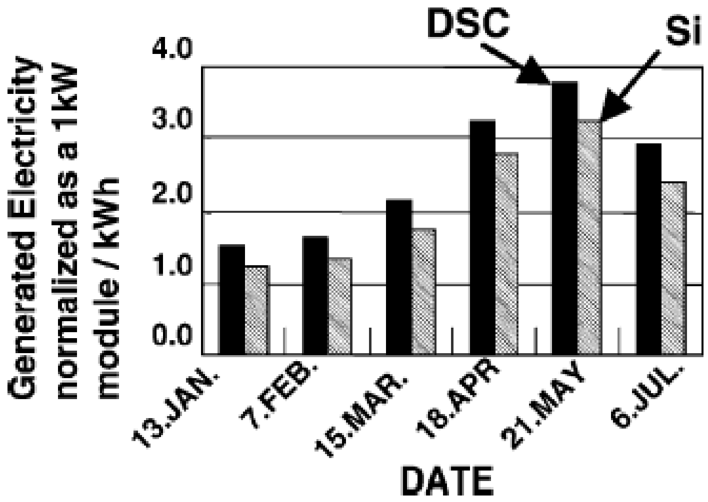


Fig. 5. Example of generated electricity for cloudy days between December and July for the DSC modules and the Si module. Output power is converted as a 1 kW module.

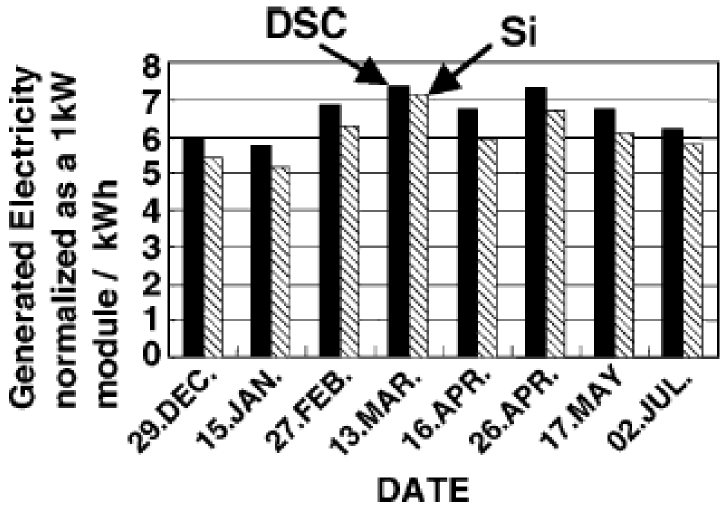


Fig. 4. Example of generated electricity for clear and sunny days between December and July for the DSC modules and the Si module. Output power is converted as a 1 kW module.

1 kWp of silicon based PV modules produce 1400 kWh / year.

1 kWp of DSC based PV modules produce 1600 kWh / year

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.

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

A continuous Glass Façade WITHOUT PV costs 1000 euro/sqm


Schott solar

DYEPOWER Consortium

PERMASTEELISA GROUP

UNIVERSITA' degli STUDI di ROMA TOR VERGATA

POLOSOLAREORGANICO RegioneLazio

ERG

DYEPOWER

UNIFE

DYESOL

UNIVERSITÀ DEGLI STUDI DI TORINO

ALMA UNIVERSITAS TAURINENSIS

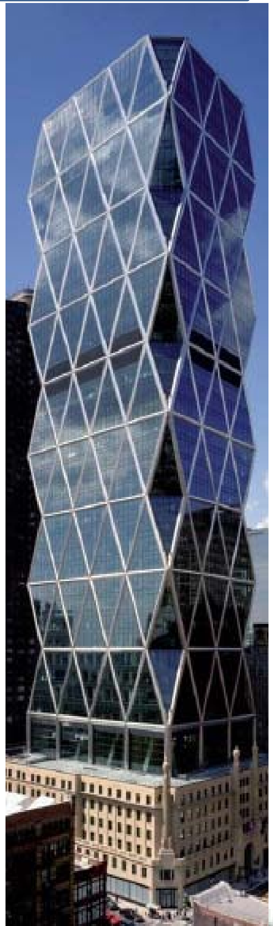
1 July 2009: Dyepower Consortium has been established

DYEPOWER: Objectives

The objective of the consortium is the development of an industrial manufacture capability for the fabrication of DSC panels particularly for photovoltaic glass building envelope. This involves identifying materials, processes and technological solutions that will enable these panels to reach the appropriate levels of cost effectiveness, stability and energy efficiency.

Main Milestones

- Prototype of Photovoltaic Glass Envelope based on DSC technology
- Pilot Plan for the production of such DSC Photovoltaic Glass Envelope



Material Costs

Material	Actual Cost / m2
Glass + TCO (2x)	25,00 €
TiO2 paste	~~20,00 €~~ → 7 euro
Pt paste	3,00 €
Dye	~~30,00 €~~ → 5 euro
Sealing paste	2,00 €
Conductive paste	4,00 €
electrolyte	~~10,00 €~~ → 3 euro
external sealing	5,00 €
other	1,00 €
TOT.	100,00 €

In few years
after material scaling up

TOT 55 euro

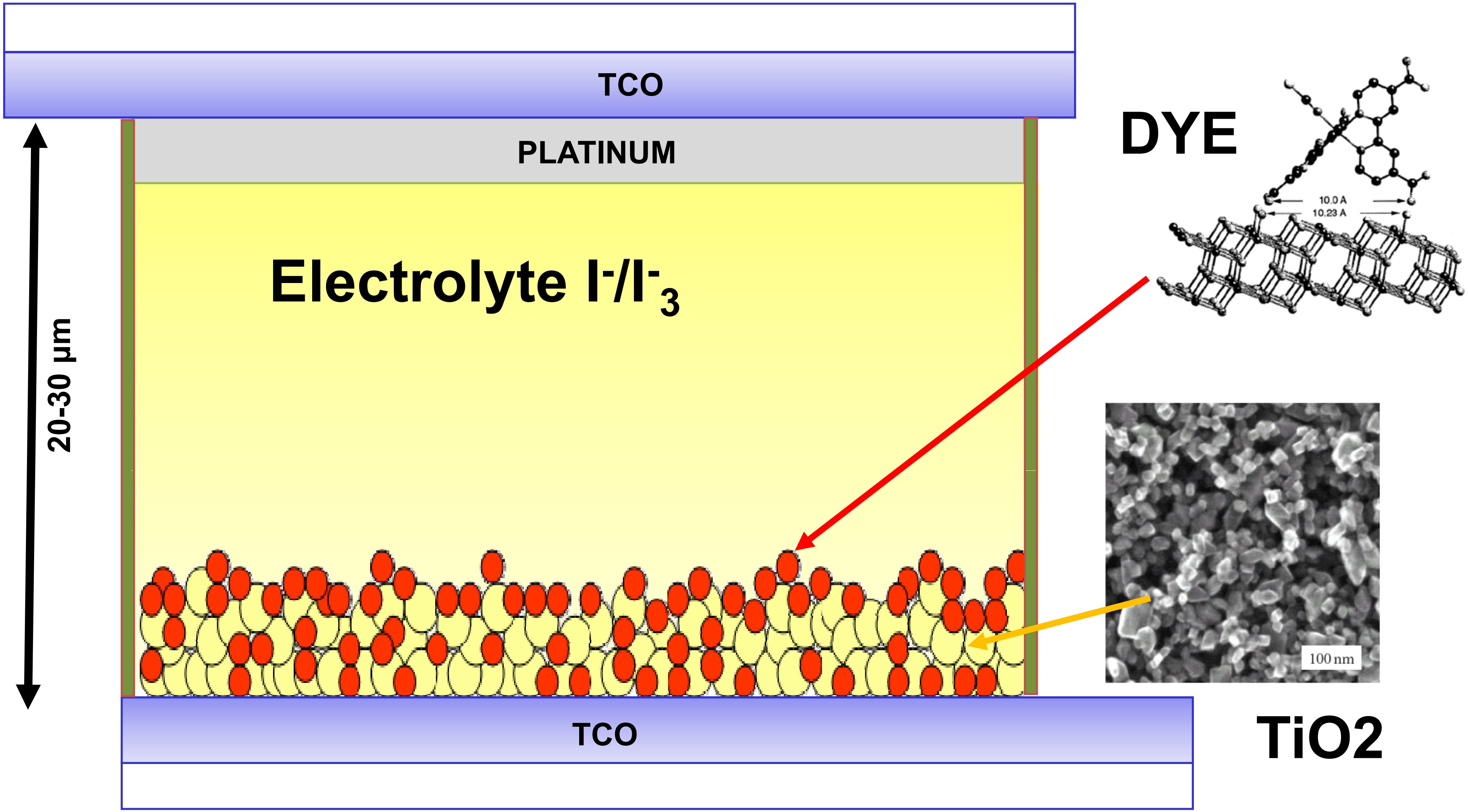
For 50 W / m^2 panel we have a cost of 2 euro/watt of materials considering an annual production of 10.000 m^2.
This reduces to 1.6 euro/Wp for a production of 100.000 m^2

Dye, TiO2 paste and Electrolytes are under industrial scaling up and we expect a strong reduction of their retail prices (< 1 euro/watt).

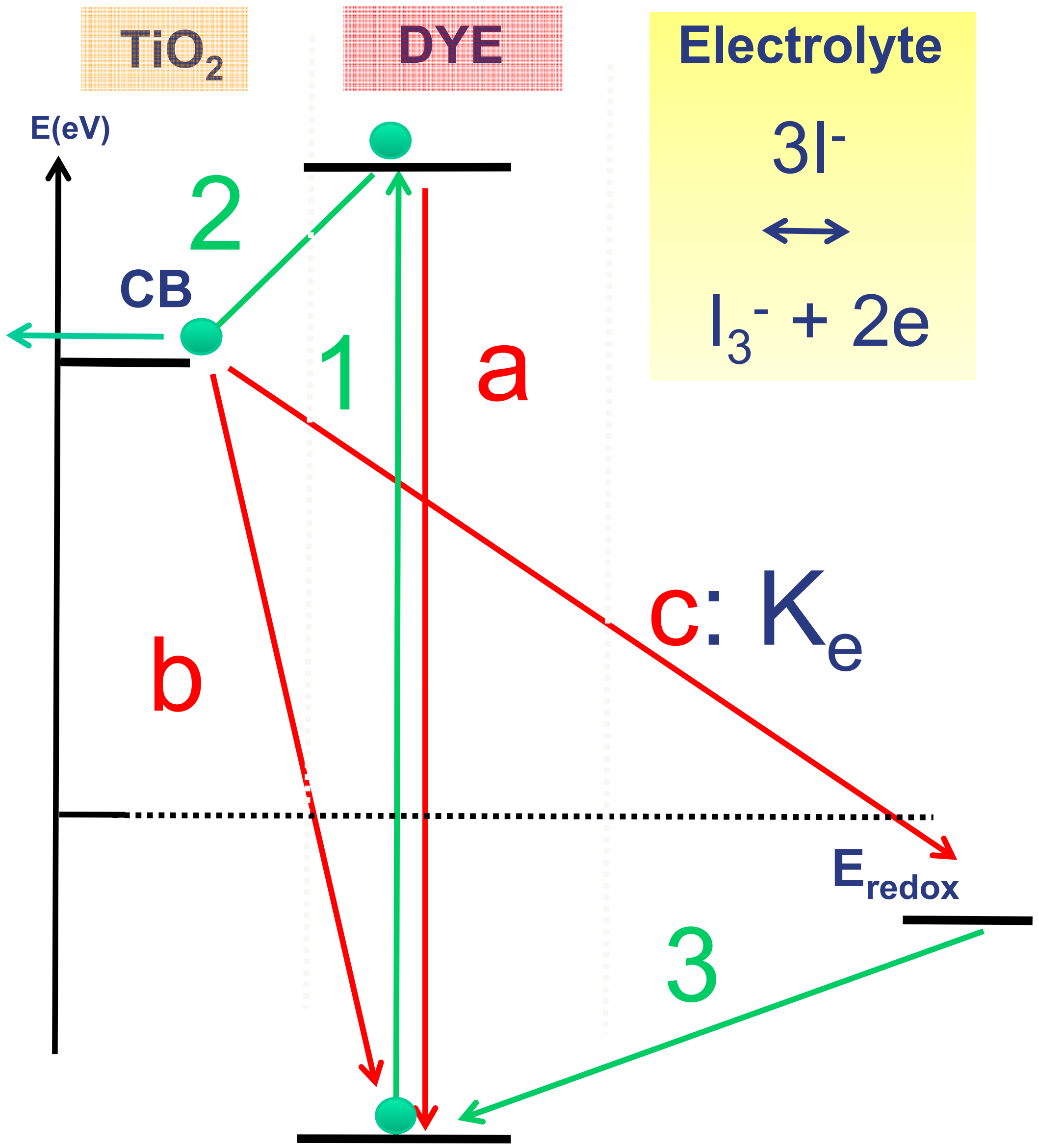
More critical is the situation for the glass-TCO where no strong reduction of the price is forecast (Pilkington)

Computer Aided Design (CAD): Simulation of DSCs

Scheme of a DSC



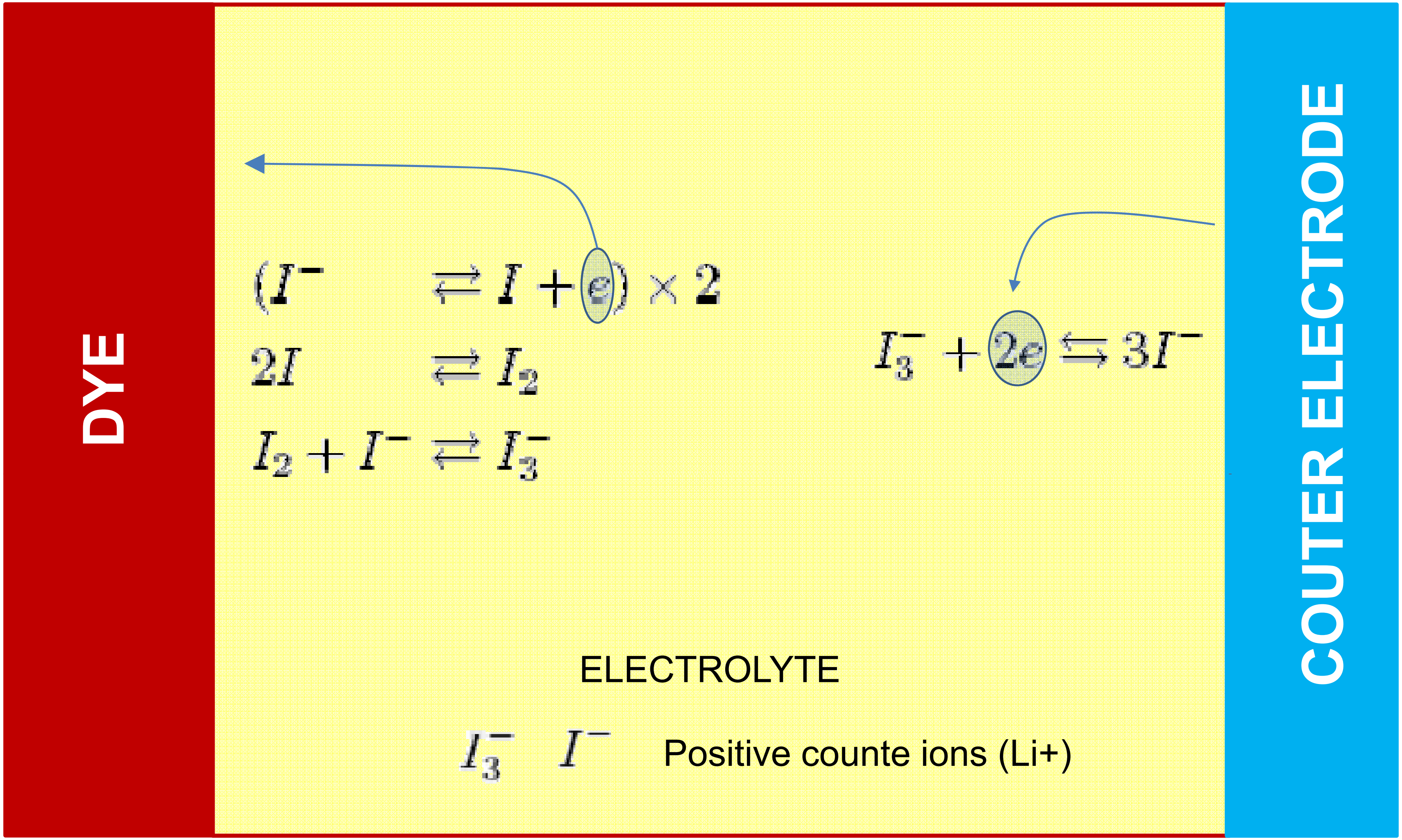
Kinetic: Important rate constants



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

Oxidation-Reduction reactions



Transport: a challenging issue

- ❖ Two different phases involved (TiO_2 and electrolyte)
- ❖ Three charge carriers contibute to the current (e, I^- ,I_3^-)
- ❖ Handling of the electrolyte regeneration at the cathode

<u>The electron in the conduction band exhibits anomalous properties:</u>

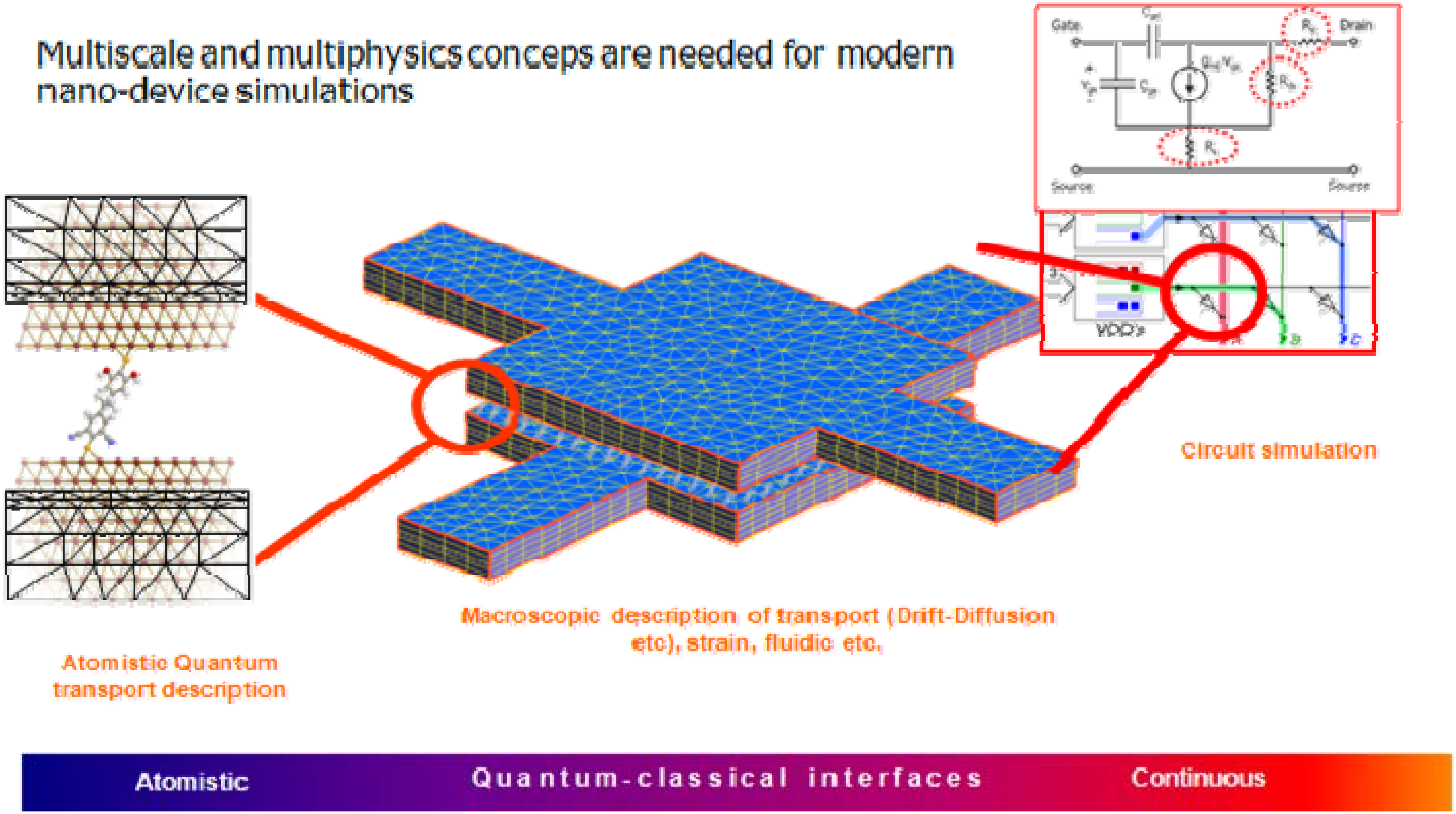
- ❖ Extremely long propagation time (ms)
- ❖ Non-exponential current and recombination transient
- ❖ Intensities-dependent response times

Physical Device Modeling - TiberCAD

DSC devices are getting complicate (3D, Tandem, Back contact etc. etc.)

TiberCAD is a multiscale device simulator : www.tibercad.org

Multiscale and multiphysics conceps are needed for modern nano-device simulations



TIberCAD have been extended to account also for simulation of DSC

Theoretical model

Cathode:

$$-e\mu_{I^-} n_{I^-}\nabla\phi_{I^-} = \frac{3}{2}\frac{V}{R_L}$$

$$-e\mu_{I_3^-} n_{I_3^-}\nabla\phi_{I_3^-} = -\frac{1}{2}\frac{V}{R_L}$$

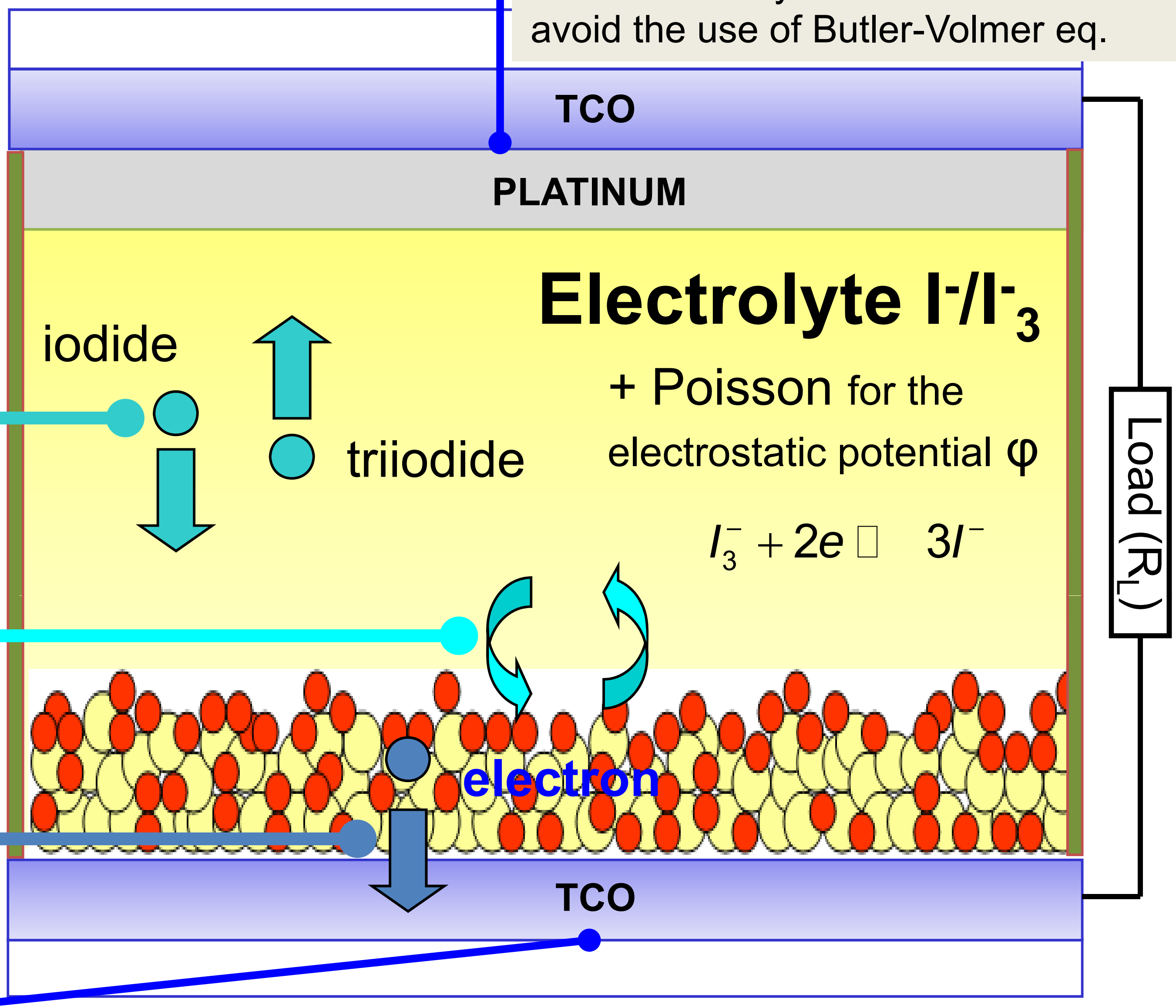
Local boundary conditions allows to avoid the use of Butler-Volmer eq.

$$\nabla\cdot\left(\mu_{I_3^-} n_{I_3^-}\nabla\phi_{I_3^-}\right) = \frac{1}{2}(R-G)$$

$$\nabla\cdot\left(\mu_{I^-} n_{I^-}\nabla\phi_{I^-}\right) = -\frac{3}{2}(R-G)$$

$$R = k_e\left[n_e\sqrt{\frac{n_{I_3^-}}{n_{I^-}}} - \bar{n}_e\sqrt{\frac{\bar{n}_{I_3^-}}{\bar{n}_{I^-}^{3}}}\,n_{I^-}\right]$$

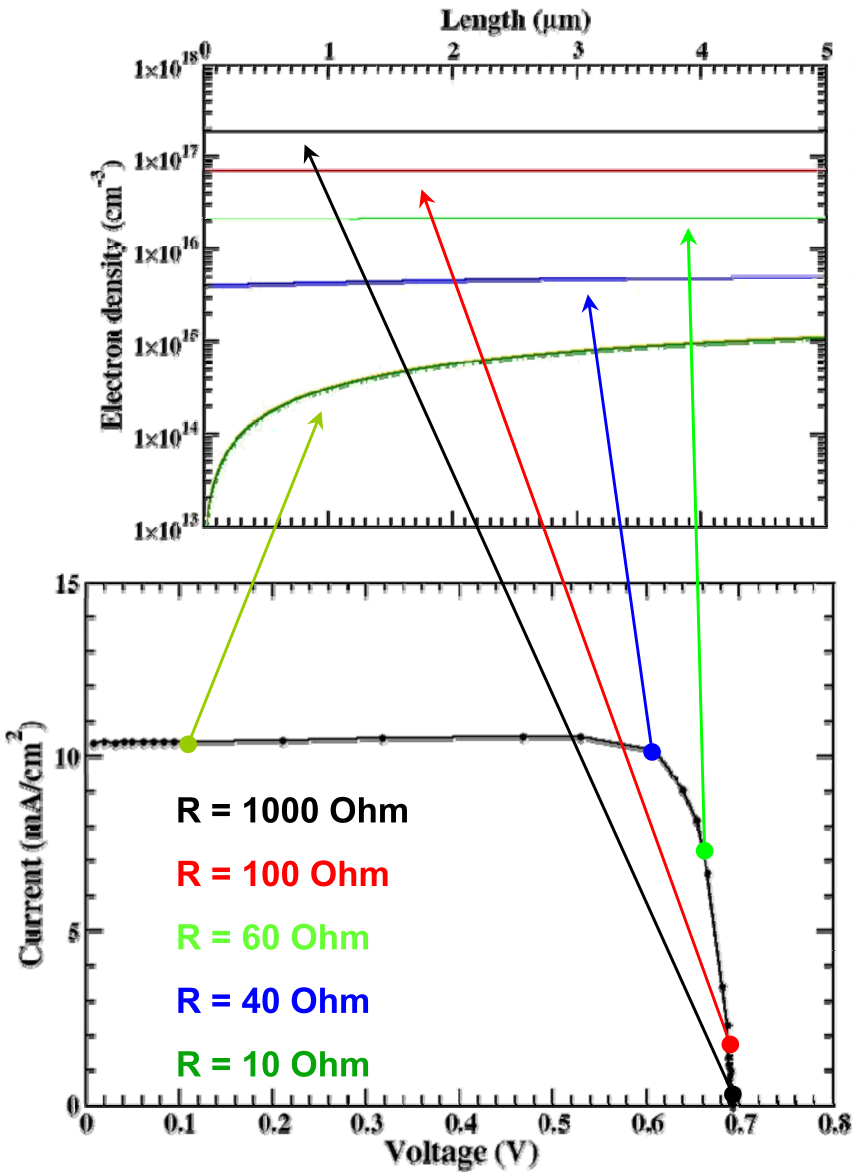
$$\nabla\cdot\left(\mu_e n_e\nabla\phi_e\right) = (R-G)$$

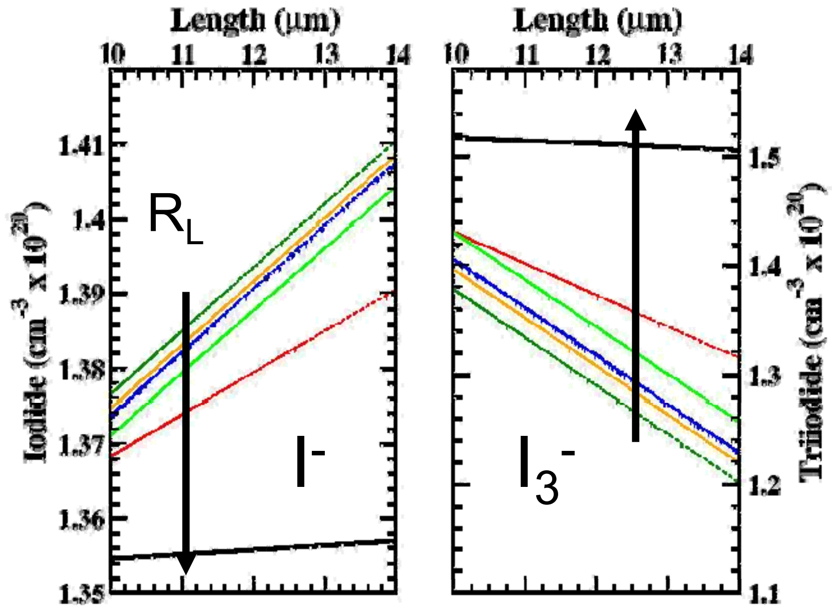


Anode: No ionic current: $\nabla\phi_{I_3^-} = \nabla\phi_{I^-} = 0$ Ohmic contact: $\nabla\varphi = 0$

Diffusion driven device

❖ The DSC is driven by a concentration unbalance between electrons and redox pair induced by the illumination. The drift component is negligible.





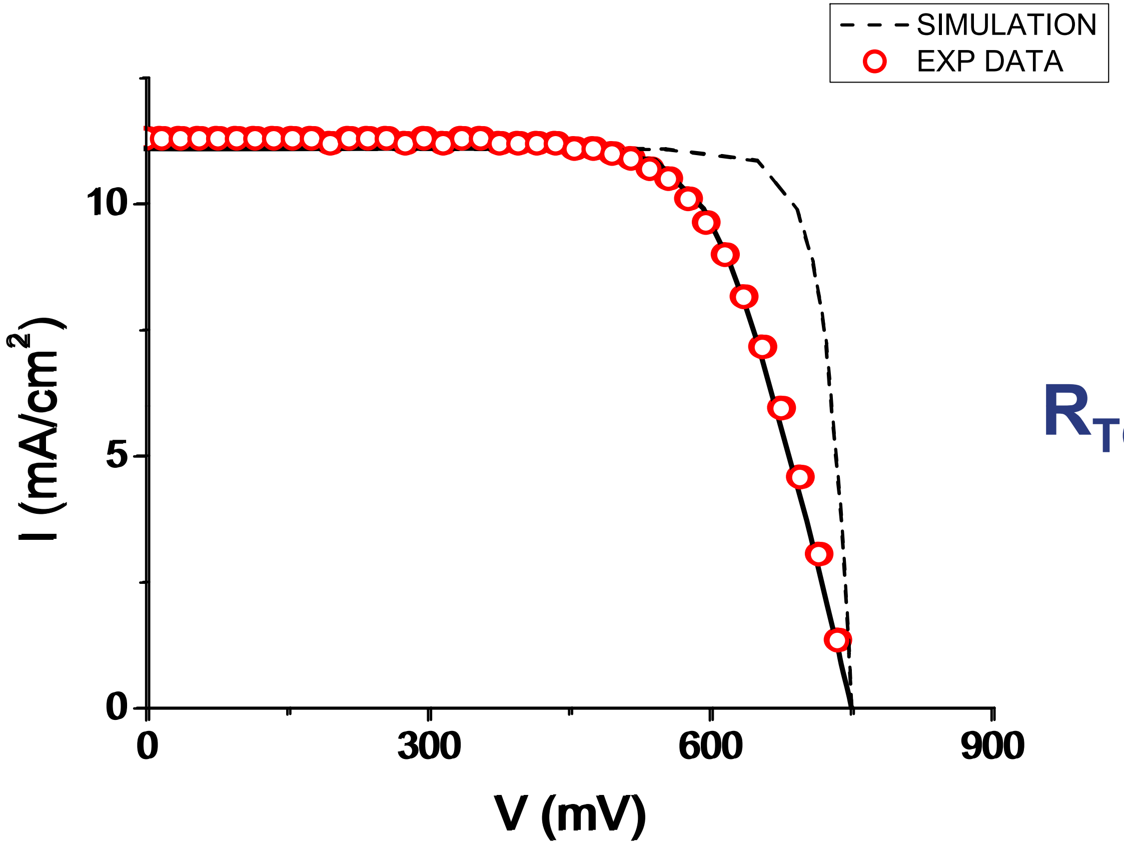
Concentration profile in the electrolyte region close to the cathode

❖ The effect on the redox pair is much smaller due to the larger concentration. On the other hand the bottleneck results to be the electrons in the oxide.

Fit to experimental data

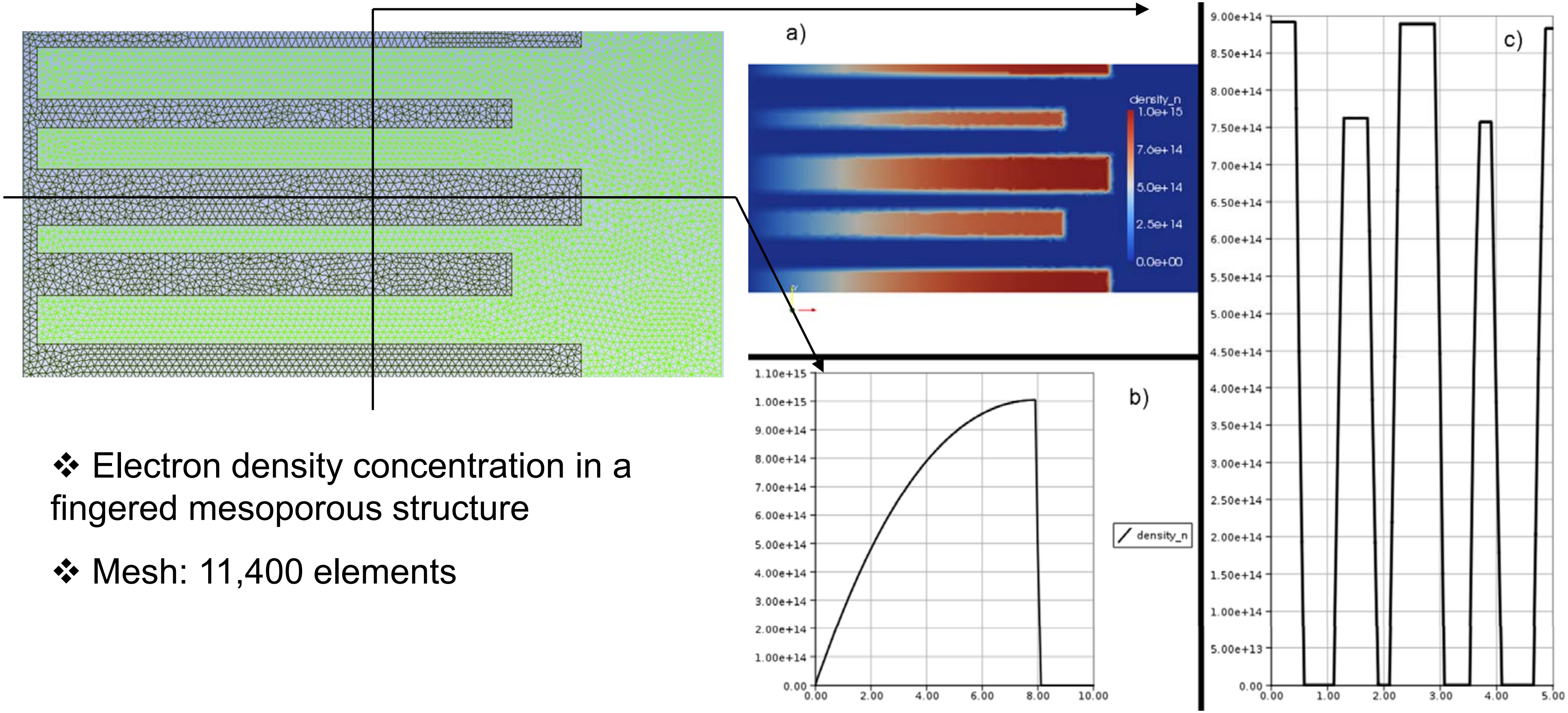
Fitting of sperimental I-V curve of a standard cell (10 µm)

PARAMETERS: μ_e**=0.8 cm²/Vs**
K_e**=10³ 1/s**



R_{TCO} 10Ω

From 1D model to 2D…

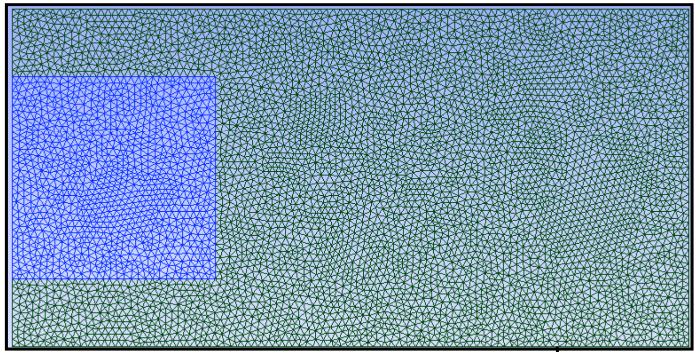


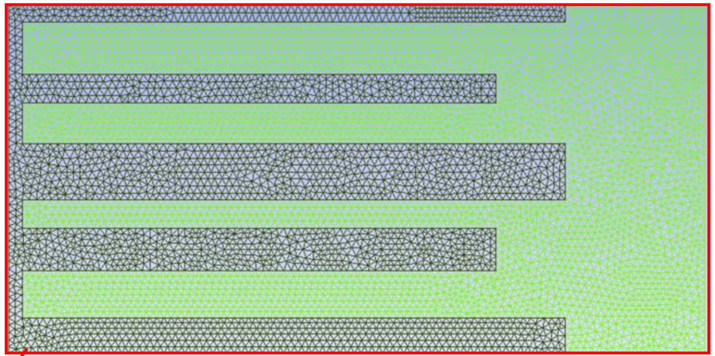
❖ Electron density concentration in a fingered mesoporous structure

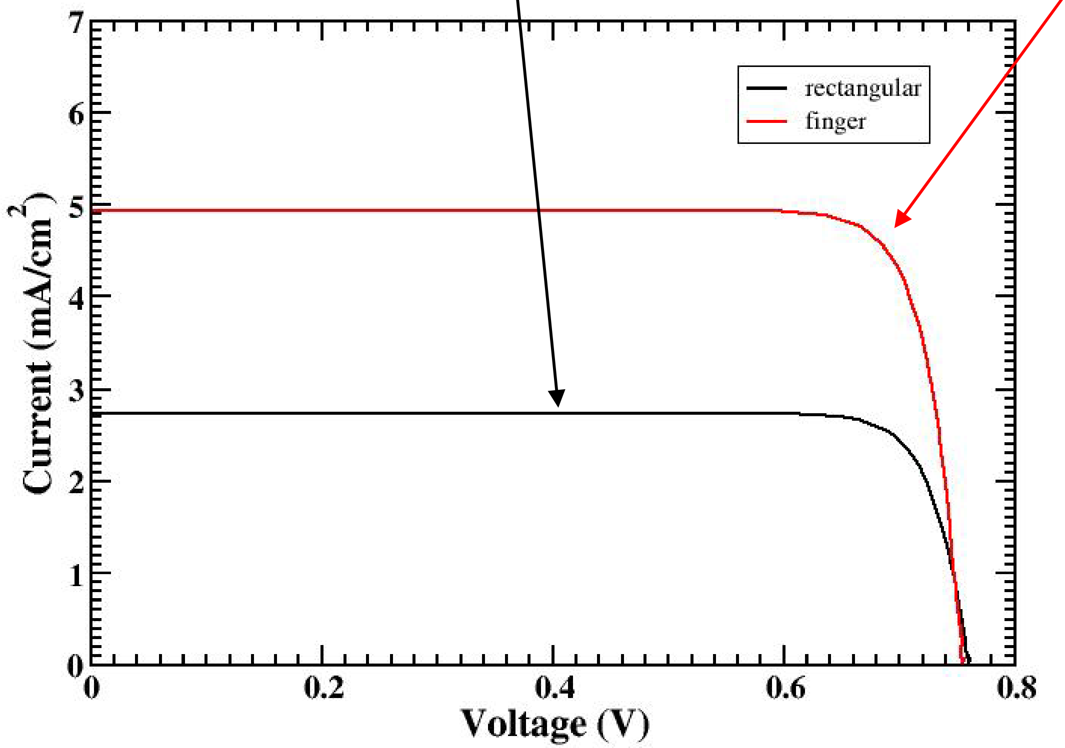
❖ Mesh: 11,400 elements

Several different topology can be investigated, with particular interest to the shape of the titanium oxide and the position of the photoanode and platinum layer.

From 1D model to 2D…





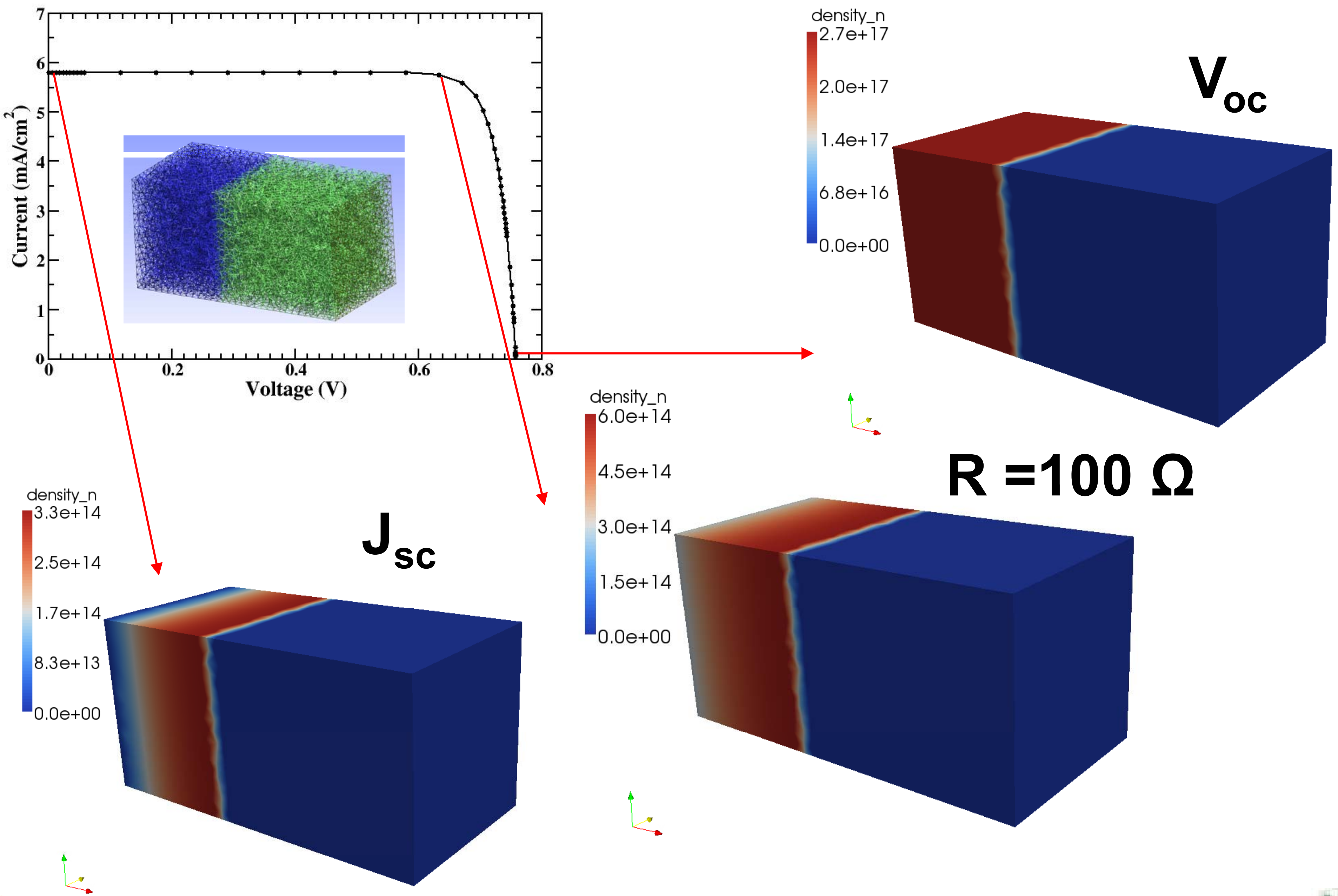


❖ Interesting effects can be seen changing the topology of the cell, especially the titanium oxide

❖ two different geometries are shown with the same parameters but different topology

❖ The lack of TiO2 for the rectangular geometry reduces the total current

…. up to 3D


Current (mA/cm2)
Voltage (V)
0
0.2
0.4
0.6
0.8
1
2
3
4
5
6
7
density_n
2.7e+17
2.0e+17
1.4e+17
6.8e+16
0.0e+00
V_{oc}
density_n
6.0e+14
4.5e+14
3.0e+14
1.5e+14
0.0e+00
R =100 Ω
density_n
3.3e+14
2.5e+14
1.7e+14
8.3e+13
0.0e+00
J_{sc}

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

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