High efficient Dye sensitized and Organic solar cells: A new perspective to the solar energy

A challenge for new market on PV cells

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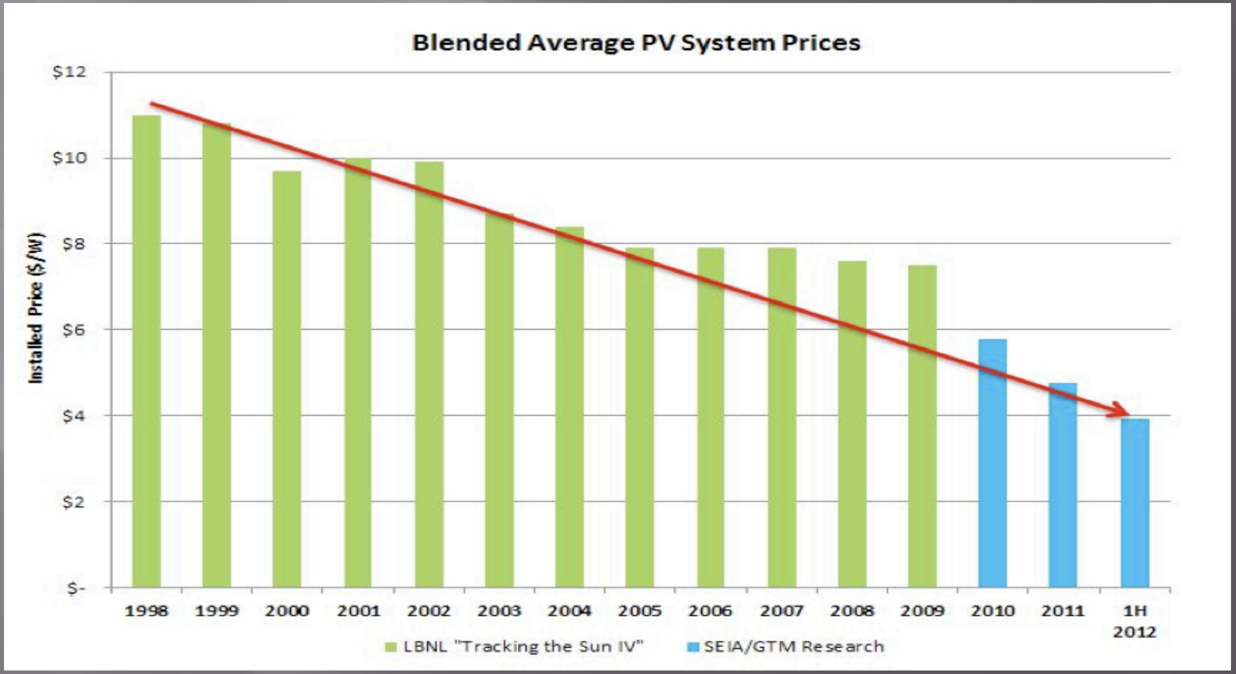
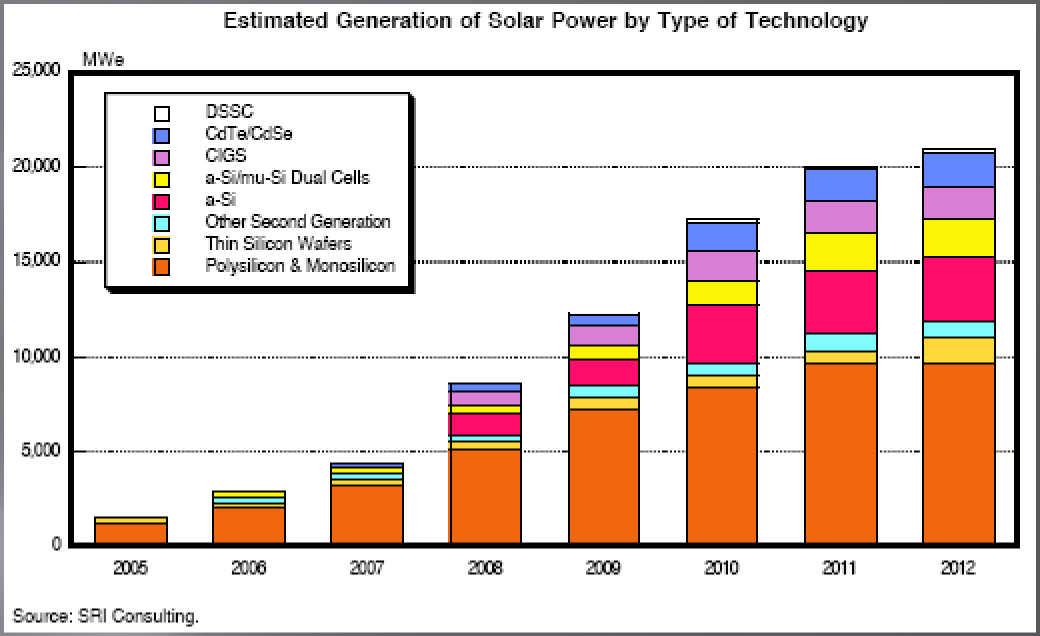
Solar energy

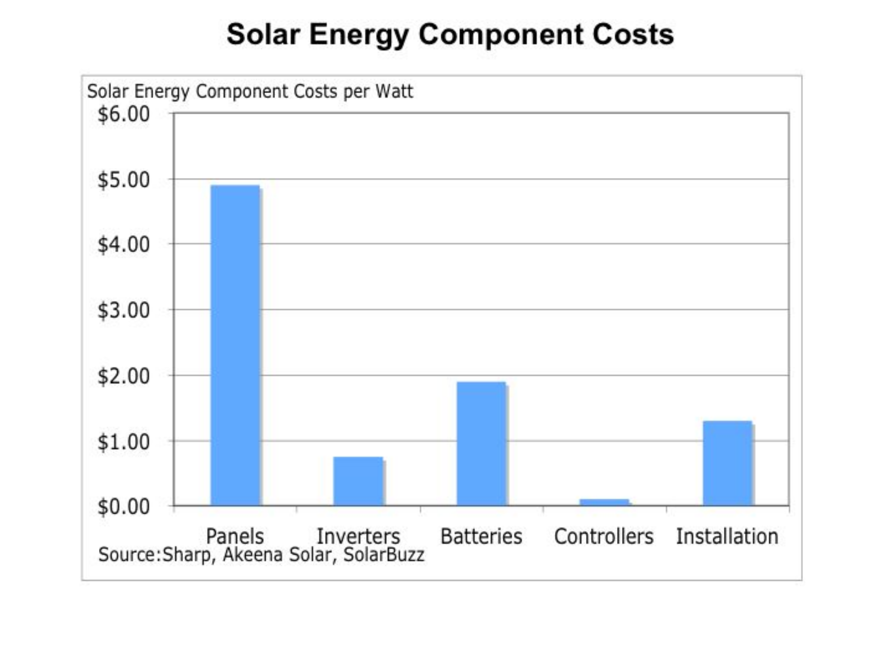
At earth's surface average solar energy is ~ 4 x 1024 J / year
Global energy consumption (2012) was ~ 5 x 1020 J / year (increasing annually~ 2%)

In US, average power requirement is 3.3 TW.
With 10% efficient cells we need 1.7% of land area devoted to PV (~ area occupied by interstate highways)



Production and cost of PVs installation





We have to find new technologies in renewable energy sources

History

- 1839 : Finding of Photovoltaic effect with liquid (Edmond Becquerel)
- 1876 : Photovoltaic effect in a solid (Heinrich Hertz)
- 1883 : Se solar cell (C. Fritts)
- 1930 : Research of Cu_2O/Cu solar cell
- 1941 : Patent of Si solar cell (R. Ohl)
- 1954 : Crystalline Si solar cell (Bell Lab.); 4 % efficiency
- 1958 : Using as assistant power in the spaceship (Vanguard I) ; 5 mW
- 1973 : oil crisis
- 1980 : solar cell using CdTe, $CuInSe_2$,TiO_2 etc.
- 1997 : world product 100MWp
- 2000 : research of advanced materials and structures

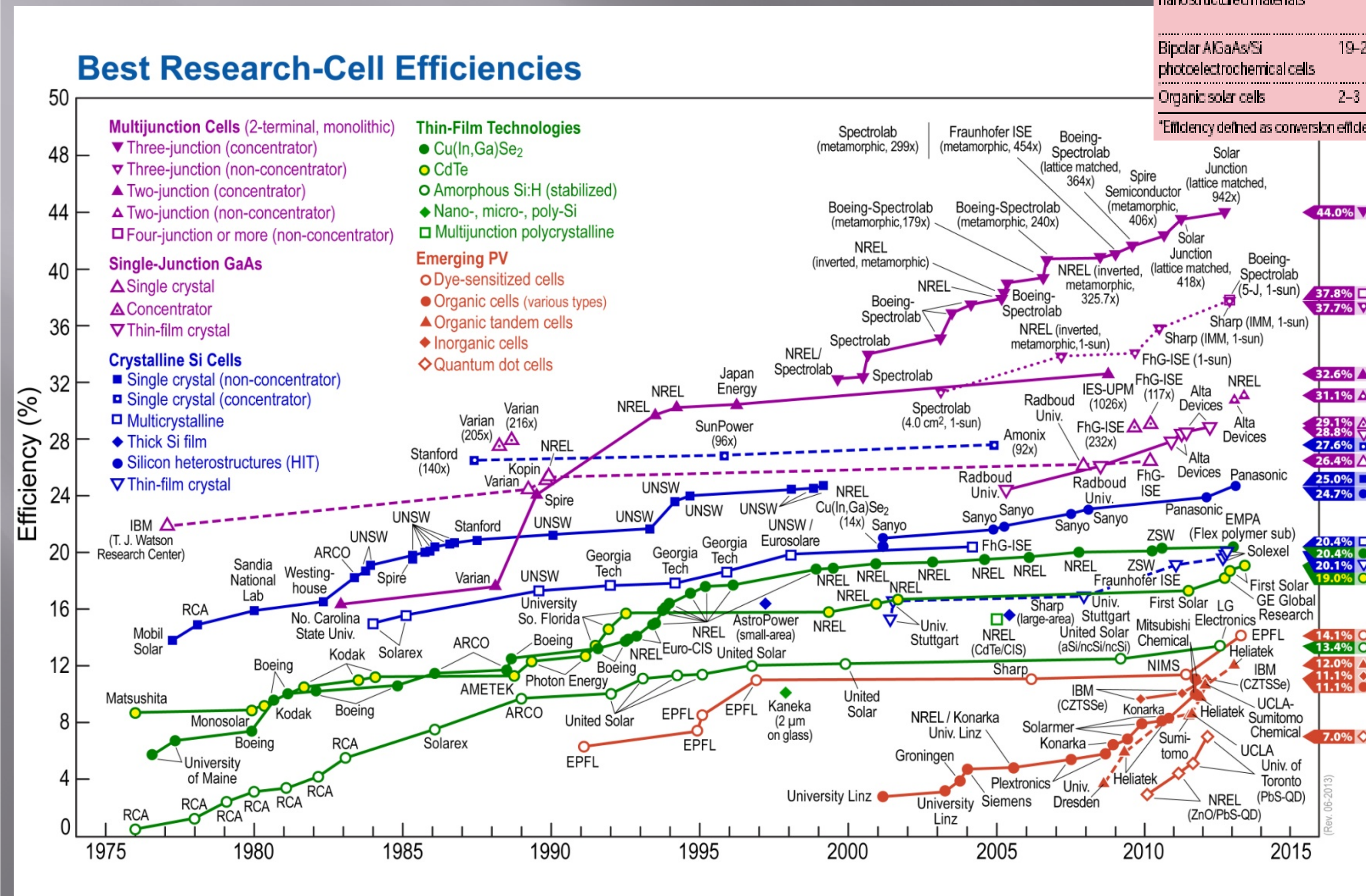
  (Dye Sensitized Solar Cell (DSSC), Organic Solar Cell (OPV))

  ➔ *cheap process , flexible substrates*

Progress of cell efficiencies

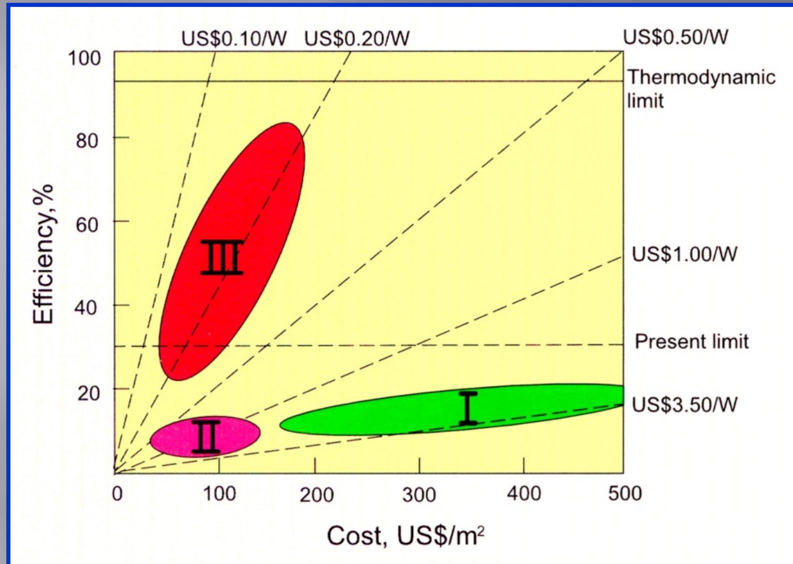
Table 1 Performance of photovoltaic and photoelectrochemical solar cells			
Type of cell	Efficiency (%)* Cell	Module	Research and technology needs
Crystalline silicon	24	10–15	Higher production yields, lowering of cost and energy content
Multicrystalline silicon	18	9–12	Lower manufacturing cost and complexity
Amorphous silicon	13	7	Lower production costs, increase production volume and stability
$CuInSe_2$	19	12	Replace indium (too expensive and limited supply), replace CdS window layer, scale up production
Dye-sensitized nanostructured materials	10–11	7	Improve efficiency and high-temperature stability, scale up production
Bipolar AlGaAs/Si photoelectrochemical cells	19–20	—	Reduce materials cost, scale up
Organic solar cells	2–3	—	Improve stability and efficiency

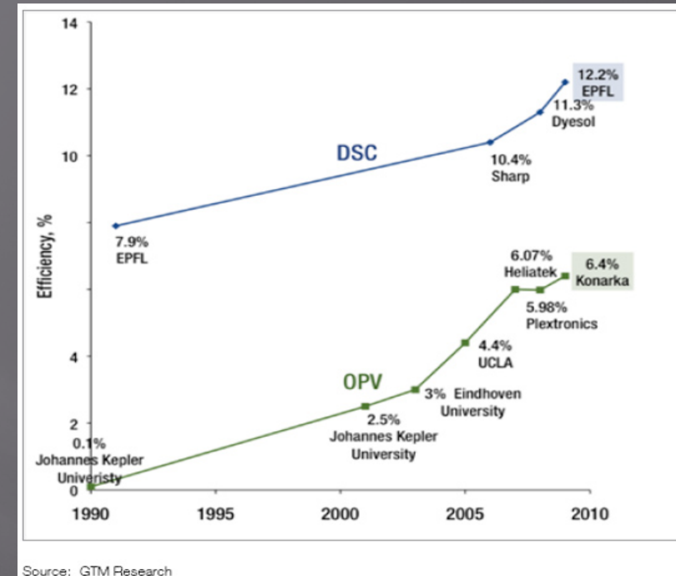
*Efficiency defined as conversion efficiency from solar to electrical power.



Under

AM 1.5G simulated solar illumination

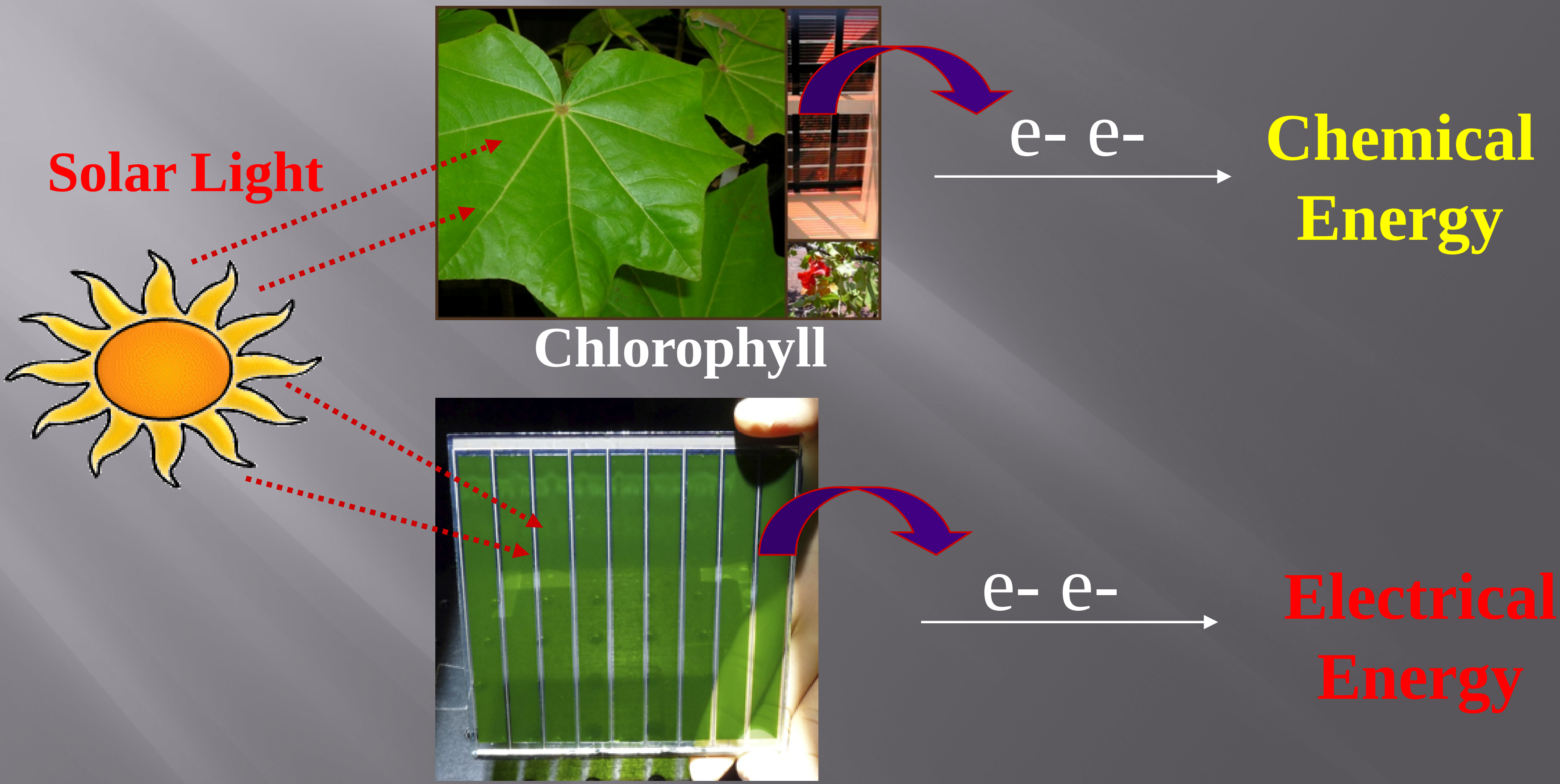




	cost	flexibility	shape factor filling	permeability	color	weight	external-internal use	efficiency
DSSC/OPV (3rd Gen)	High Advantageous	High Advantageous	High Advantageous	High Advantageous	High Advantageous	High Advantageous	High Advantageous	Medium Advantageous
Thin Film (2nd Gen)	Medium Advantageous	Medium Advantageous		Medium Advantageous	Disadvantageous	Medium Advantageous	Medium Advantageous	Medium Advantageous
Crystalline Silicon (1st Gen)	Disadvantageous			Disadvantageous	Medium Advantageous	Disadvantageous	Disadvantageous	High Advantageous

Disadvantageous — Medium Advantageous — High Advantageous

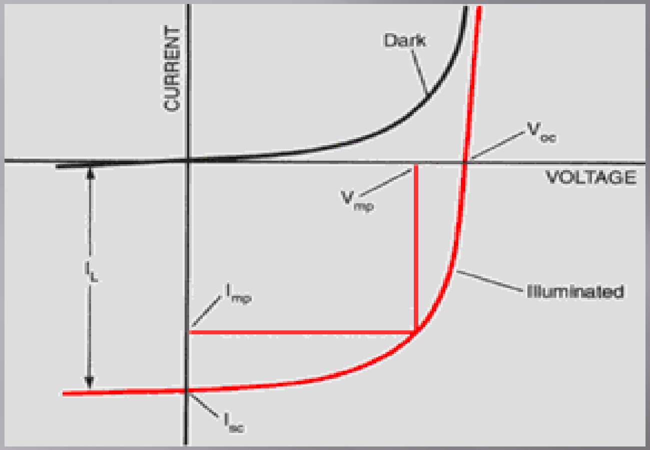
Photosynthesis and Photoelectrochemical Solar cells



Photoelectrochemical solar cell

Cell efficiency

Power conversion efficiency (η)



$$\eta = \frac{I_{mp}V_{mp}}{P_S} \times 100$$

$$\eta = \frac{I_{sc}V_{oc}FF}{P_S} \times 100$$

Under **AM 1.5G** simulated solar illumination

I_{SC} : Short-circuit current

→ Current value when V = 0

V_{OC} : Open-circuit voltage

→ Voltage value when I = 0

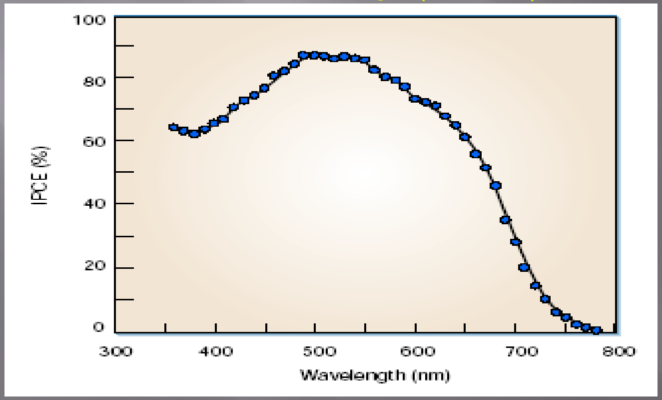
P : Power output of the cell

P = IV

FF : Fill factor

$$FF = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}}$$

Incident-photon-to-current conversion efficiency (IPCE)

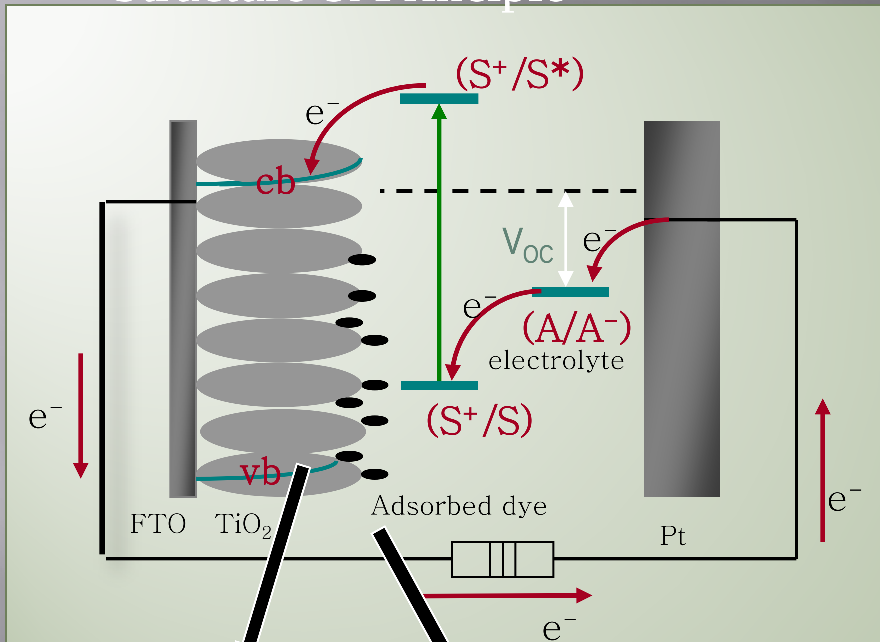


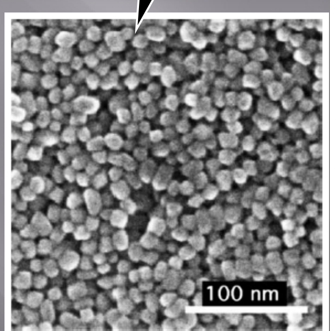
$$IPCE = \frac{\text{no. of electrons through the external circuit}}{\text{no. of photons incident}}$$

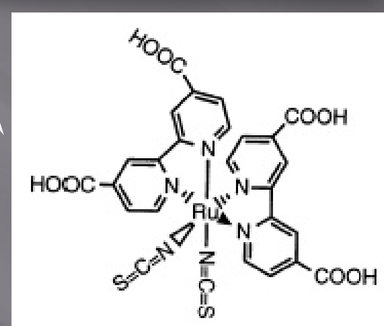
$$= \frac{[1240\ eV\ nm][photocurrent\ density\ (\mu A\, cm^{-2})]}{[wavelength\ (nm)][irradiance\ (mW\ cm^{-2})]}$$

Dye-Sensitized Solar Cell (DSSC)

Structure & Principle







Cell reactions

- $S_{(adsorbed)} + h\nu \rightarrow S^{*}_{(adsorbed)}$
- $S^{*}_{(adsorbed)} \rightarrow S^{+}_{(adsorbed)} + e^{-}_{(injected)}$
- $S^{+}_{(adsorbed)} + A^{-} \rightarrow S_{(adsorbed)} + A$
- $A_{(cathode)} + e^{-} \rightarrow A^{-}_{(cathode)}$

Advantages

Low cost (<100 euros/m^2)

Utilization of visible range of light

Simple manufacturing process

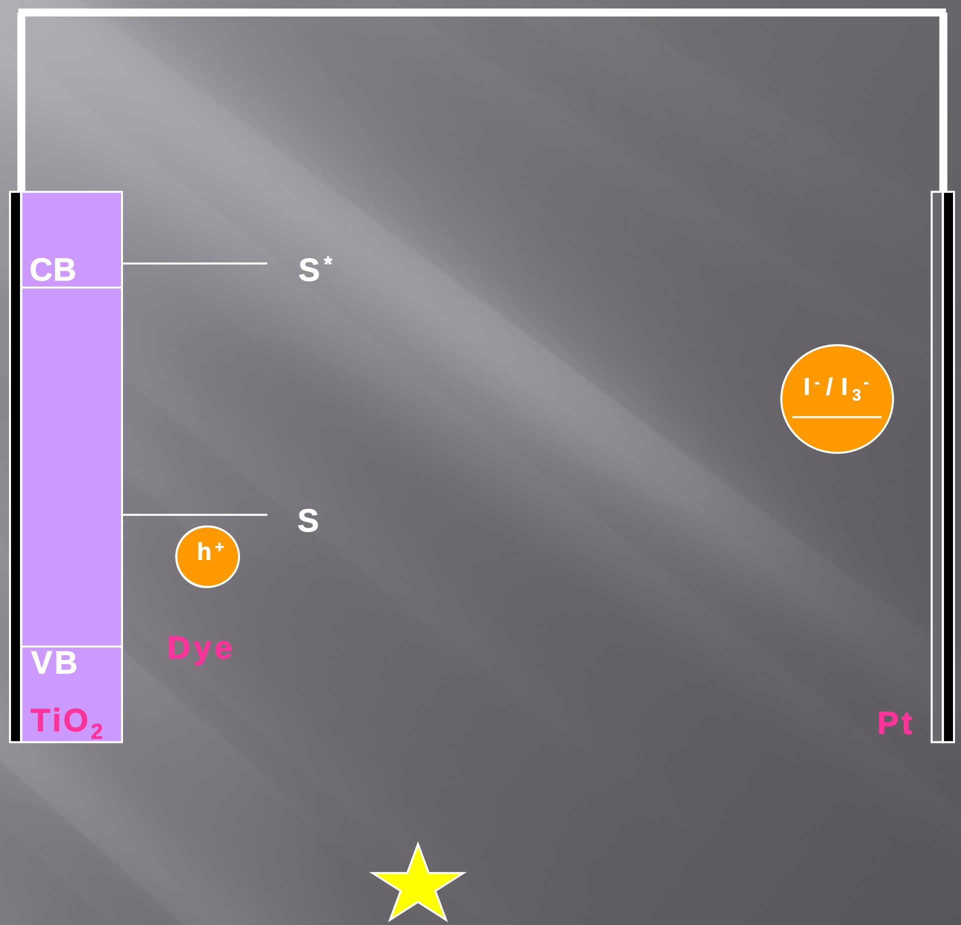
Environmental compatibility

Transparent solar cell

- Window

Moderate efficiency ~10%

Principle of Operation



Key Components

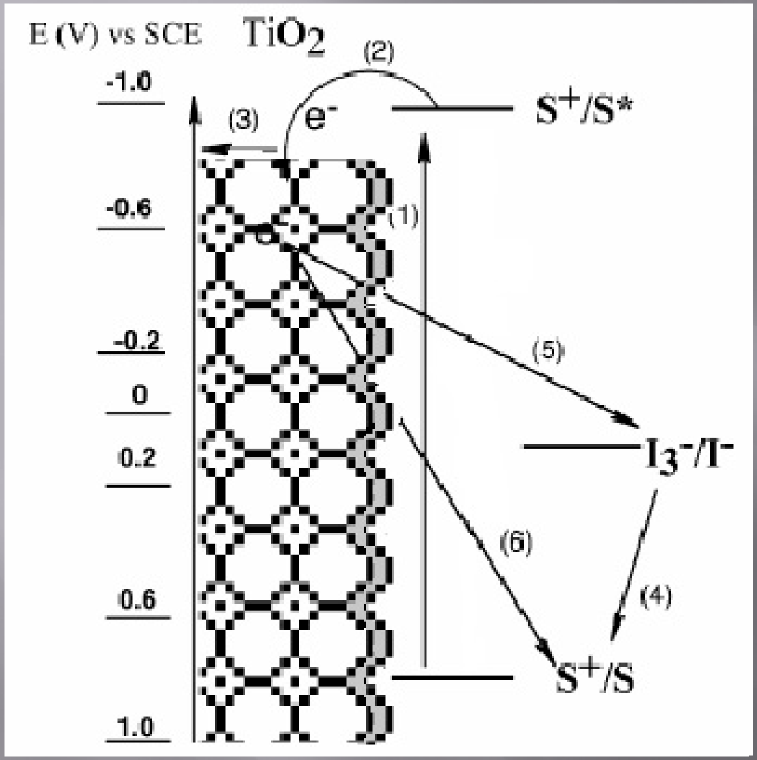
1. Nanocrystalline SC → large surface area, high porosity, pore size distribution, light scattering, electron percolation, Anatase (TiO_2), ZnO, SnO_2, Nb_2O_5

2. Sensitizers (Dye) → distribution of the dyes on the semiconductor surface, spectral properties, redox properties in the ground and excited state, anchoring groups (carboxylate or phosphonate), Polypyridyl, Porphyrins, or Phthalocyanines complexes

3. Electrolyte → ionic conductivity, electron barrier and hole conductor, redox potential, mechanical separator, interfacial contact for dye, TiO_2 and counter electrode (I^-/I_3^-)

4. Extra → transparent conductive oxide (conductivity, transmittance), sealing, metal grid, counter electrode

Dynamics



(1) Excitation of dye under illumination (ns)

(2) Electron injection (ps)

(3) Electron transport (ms)

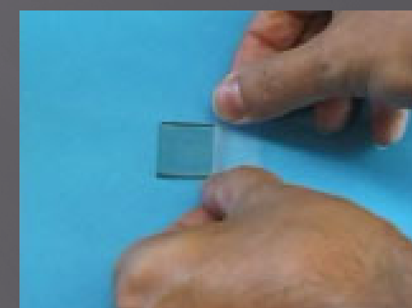
(4) Regeneration of dye (10 ns)

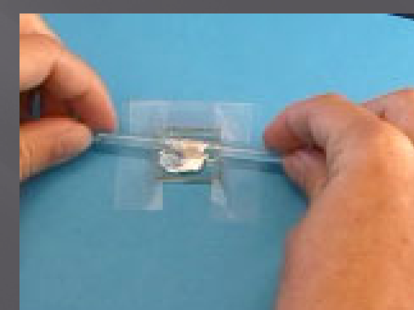
(5) Recombination with oxidized redox (ms)

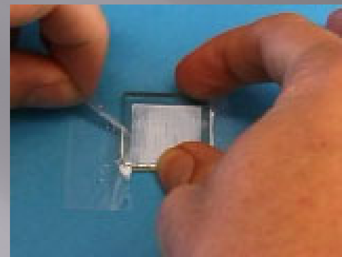
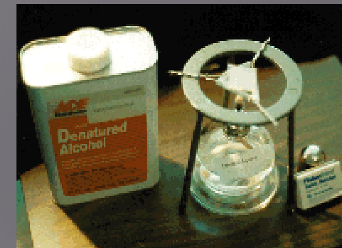
(6) Recombination with oxidized dye (s)

30 mM of I^- is enough to reduce the most of dye cations

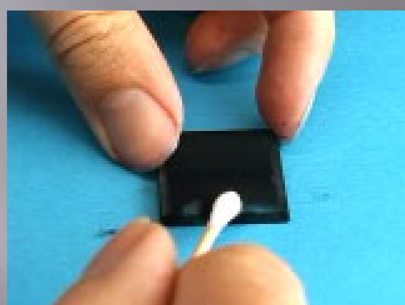
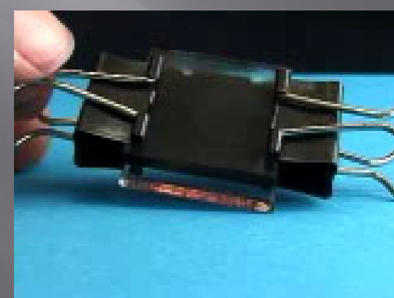
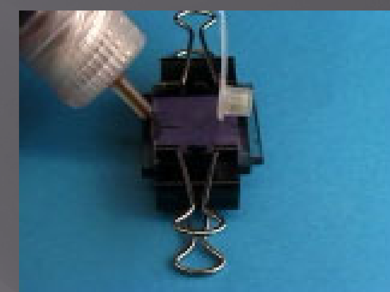
How to easily built a Dye Sensitized Solar cell







Denatured
Alcohol



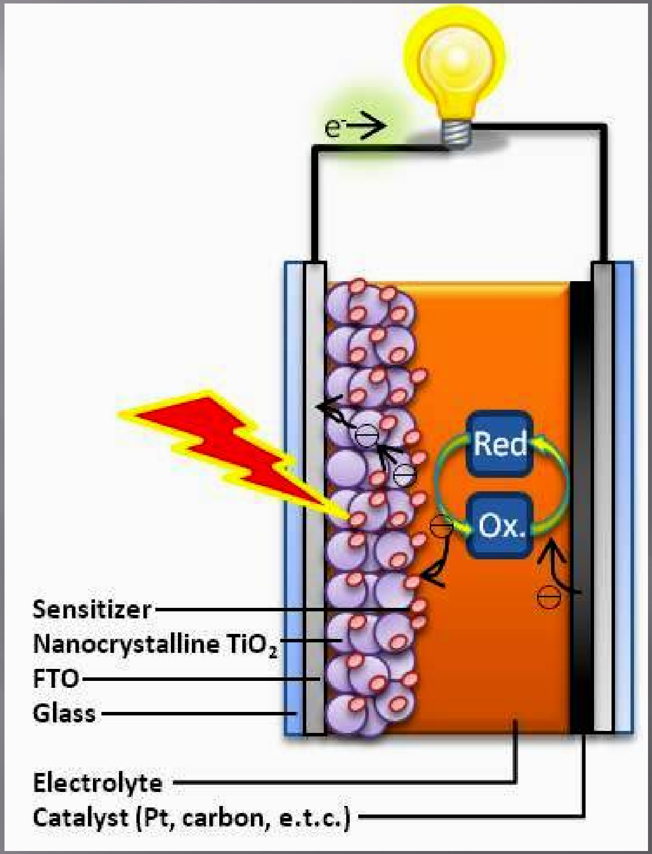
GoldStar
.4085


5.04

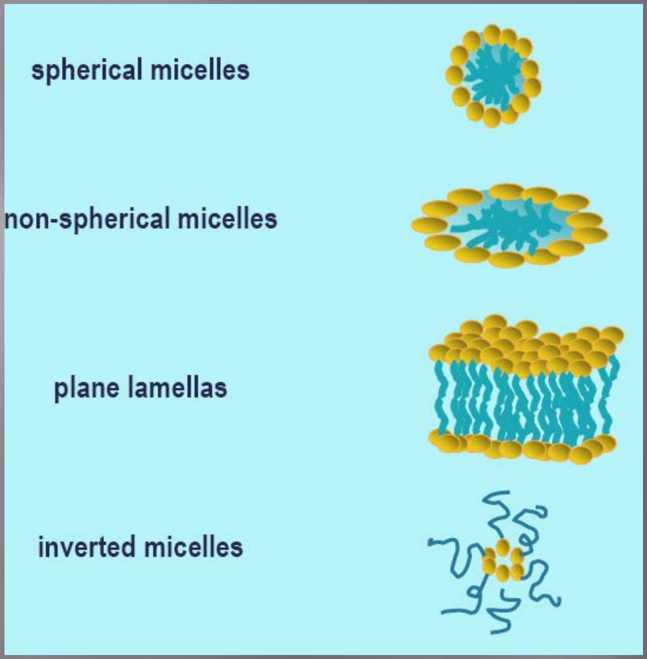
An overview to the Main process steps of Manufacturing a standard nc-DSSCell

1. Structuring (electrical insulation) of the TCO-glass plates
2. Screen-printing of conductive silver lines for adequate current collection
3. Screen-printing of colloidal TiO_2 and platinum-containing pastes on the two electrodes
4. Sintering of the TiO_2 and platinum layers between 400 and 500^oC
5. Coloration of the TiO_2 electrode by chemical bath deposition
6. Sealing/lamination of the two electrodes
7. Injection of electrolyte through the two electrodes and device closure
8. Electrical contacting and wiring

Dye-sensitized Photoelectrochemical Solar Cells based on liquid electrolytes or nanocomposite organic/inorganic gels (solid electrolytes).



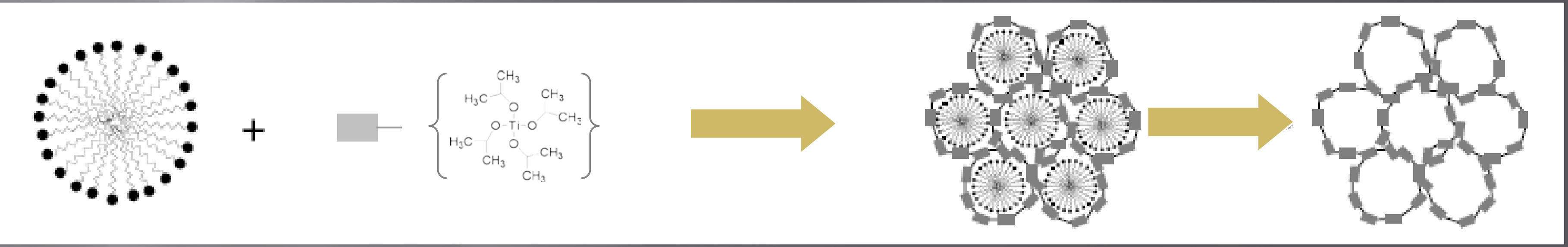
Surfactants as templates in the formation of TiO_2 nanostructure



Micelles

of Triton X-100

TiO_2 precursor

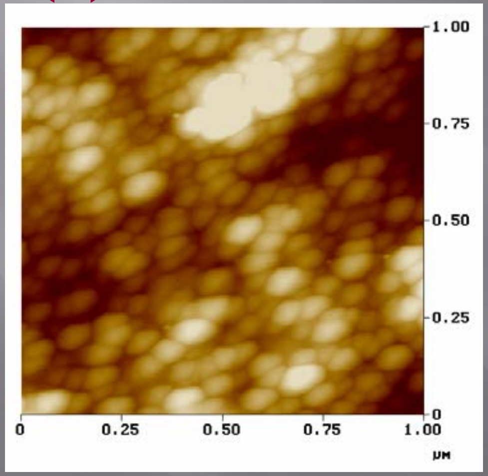


Preparation procedure of TiO_2 powder and films with TTIP precursor.

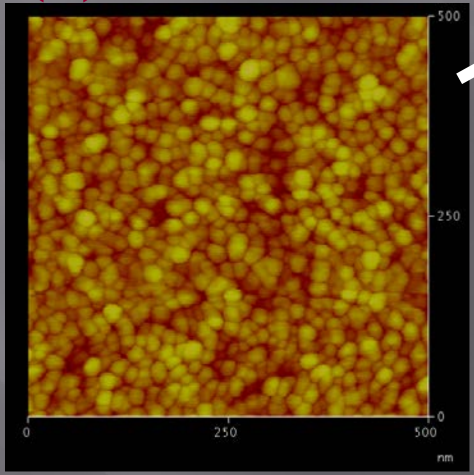
Organic acid solvolysis

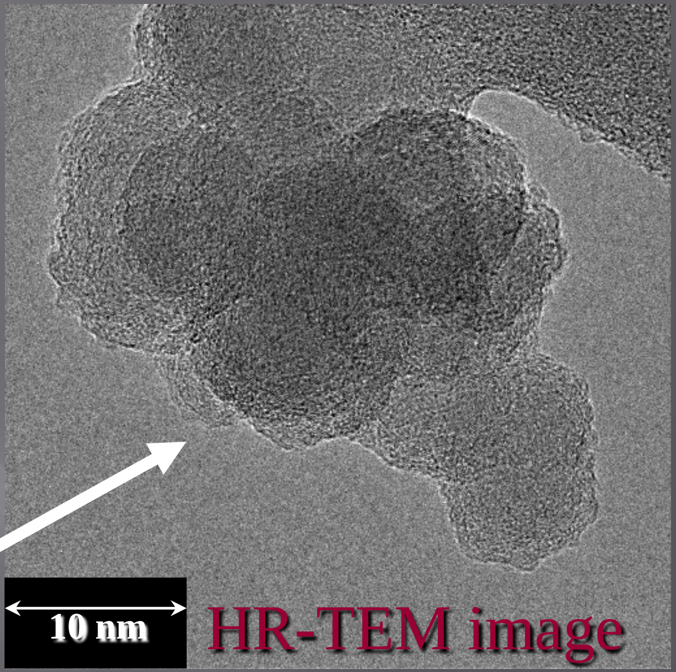
Ti-OR + AcOH → Ti-OAc + ROH
ROH + AcOH → ROAc + H_2O
Ti-OAc + ROH → ROAc + Ti-OH
Ti-OR + Ti-OAc → ROAc + Ti-O-Ti

(a) ~ 50 nm

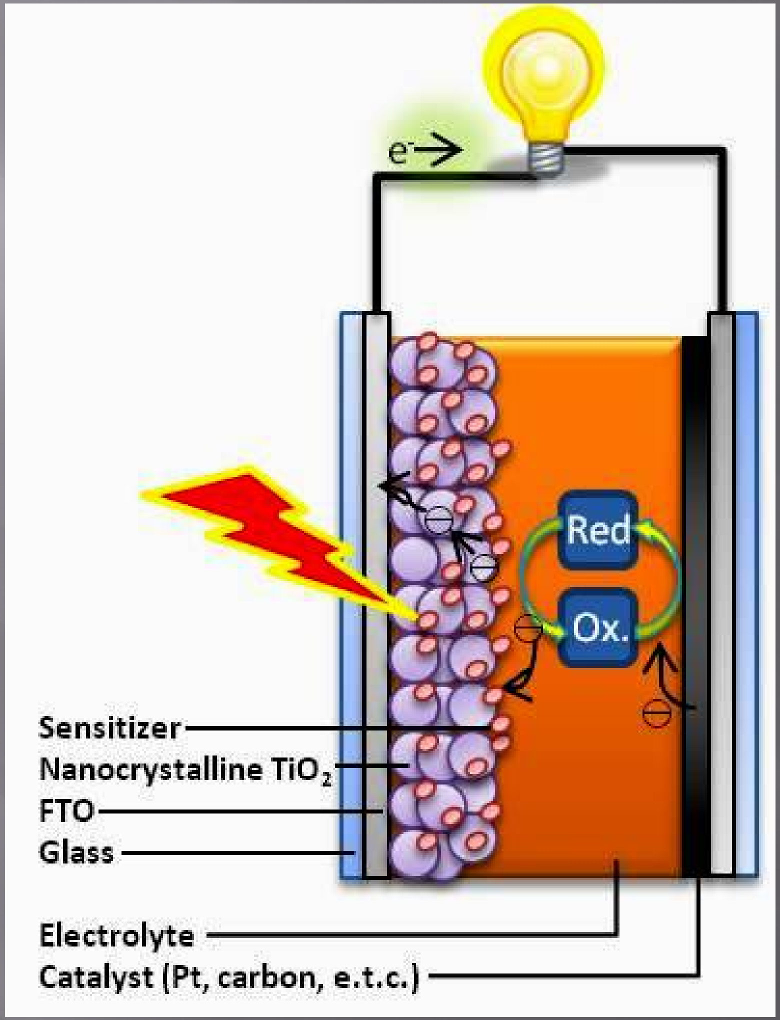


(b) ~ 15 nm

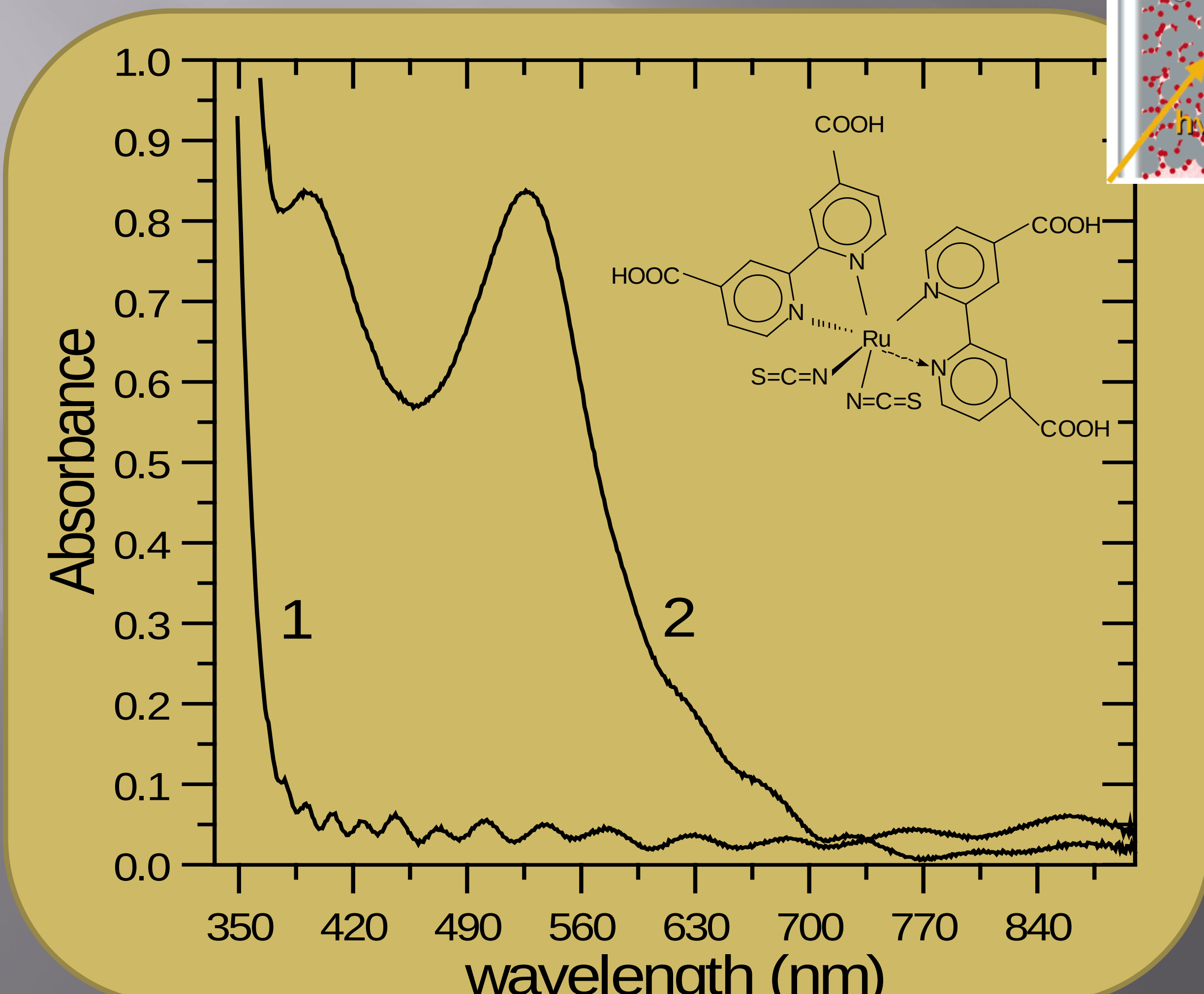


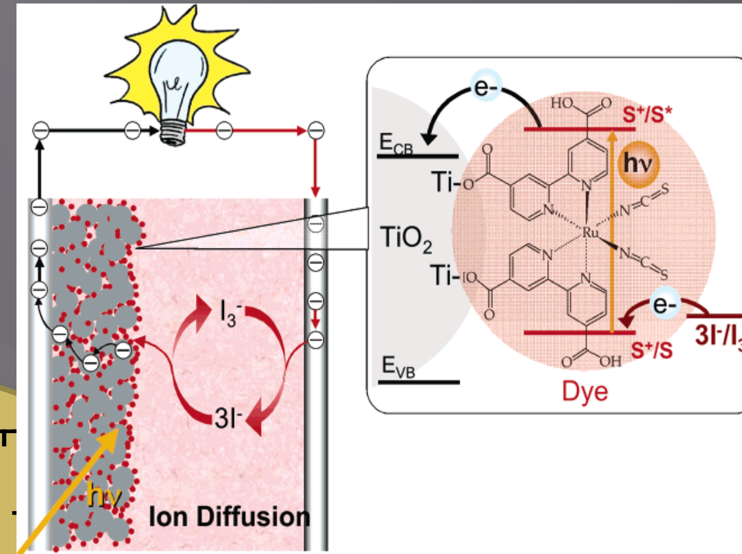


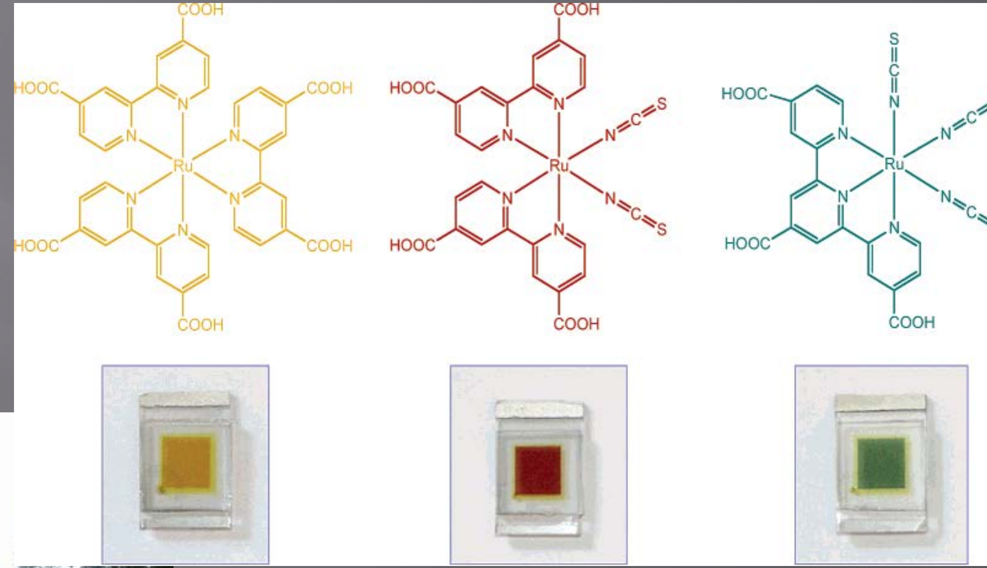
Varying organic Template (a) PEG 2000 and (b) Triton X-100

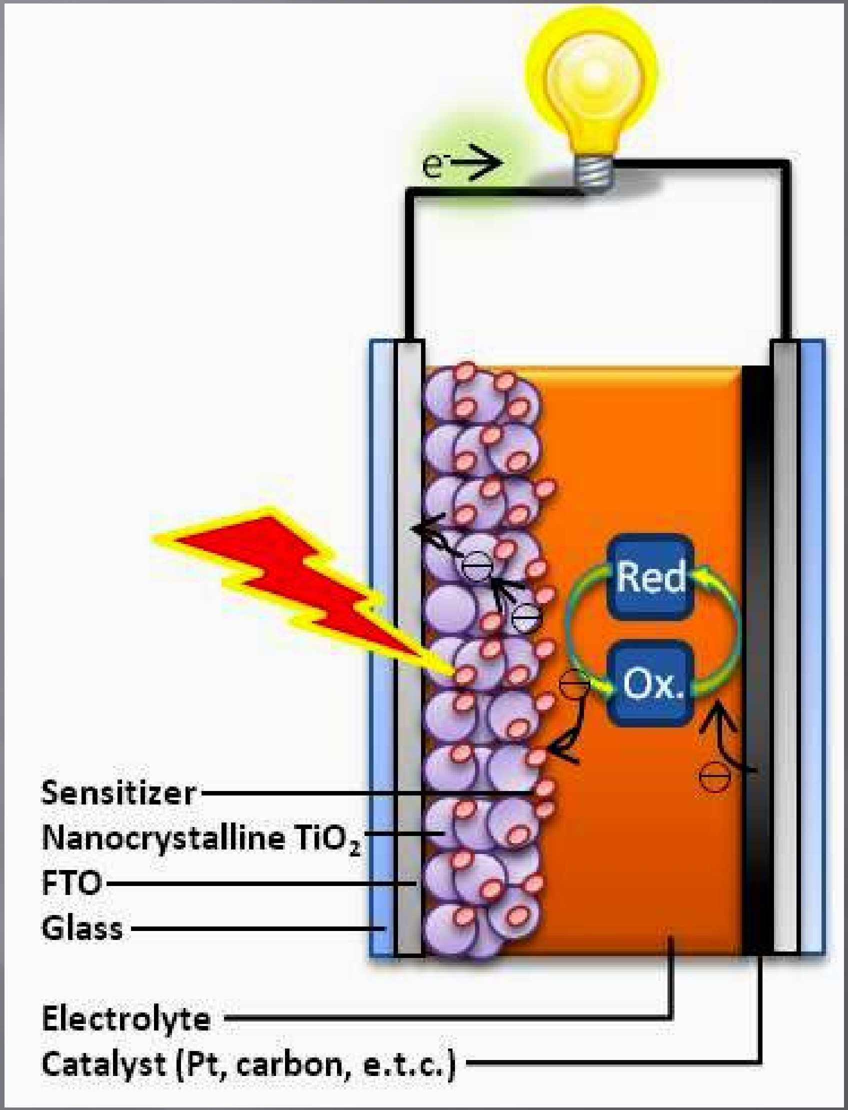

e⁻
Red
Ox.
Sensitizer
Nanocrystalline TiO_2
FTO
Glass
Electrolyte
Catalyst (Pt, carbon, e.t.c.)

TITANIA FILM AND ADSORBED DYE-SENSITIZER








e⁻
Red
Ox.
Sensitizer
Nanocrystalline TiO2
FTO
Glass
Electrolyte
Catalyst (Pt, carbon, e.t.c.)

Liquid electrolyte is usually the redox couple I^-/I^-_3 from a mixture of KI/I_2 in an organic (no viscous) solvent (acetonitrile – sulfolane – propylene carbonate)

More efficient ionic transportation but we have sealing problems

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COMPOSITION OF A NANOCOMPOSITE ELECTROLYTE

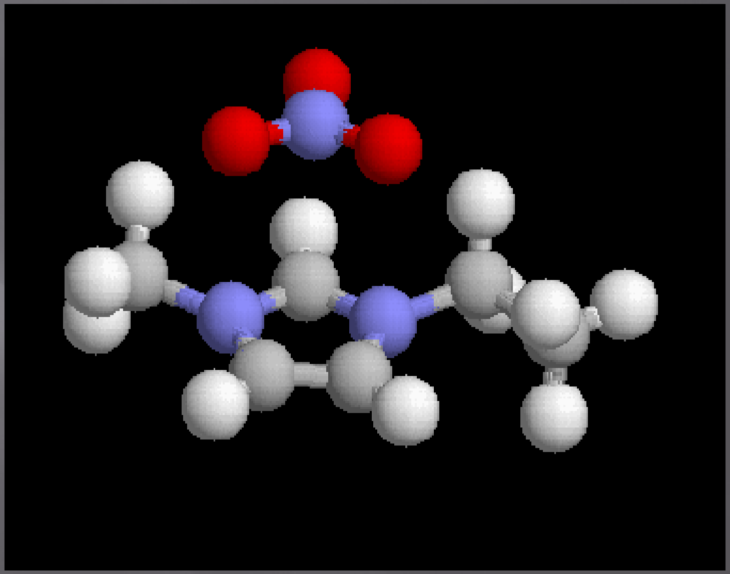
1. **Organic-inorganic matrix**
2. **Solvent**
2. **Redox couple I^-/I_3^-**

The precursor solution must be sufficiently fluid to fill the pores of the nanostructured semiconductor

Nanocomposite organic–inorganic materials prepared through Sol-Gel method give a new type of Solid State Electrolytes with excellent durability and mechanical properties.

Room Temperature Ionic Liquids (RTILs)

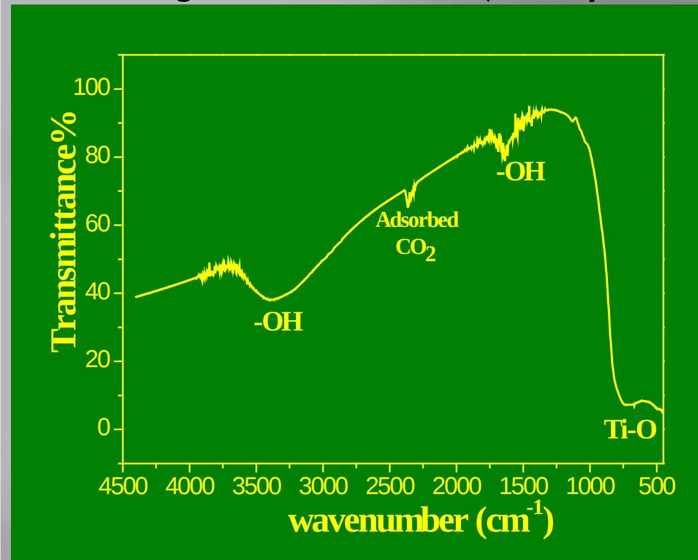
- A RTIL is an ionic material that is liquid at room temperature.
- They are based primarily on asymmetric organic cations paired with inorganic anions.
- By changing the ions, a countless variety of RTILs can be obtained.
- The asymmetric shape of the cations prevents the packing and the formation of solids at room temperature.
- Air and water resistant.
- Can be hydrophilic or hydrophobic.



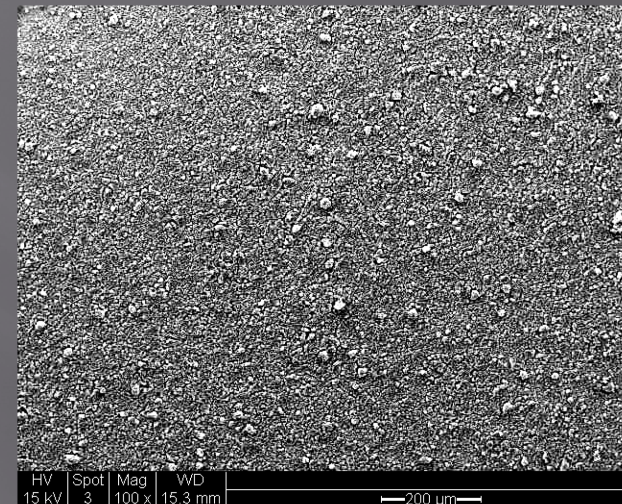
TiO_2 prepared in room temperature

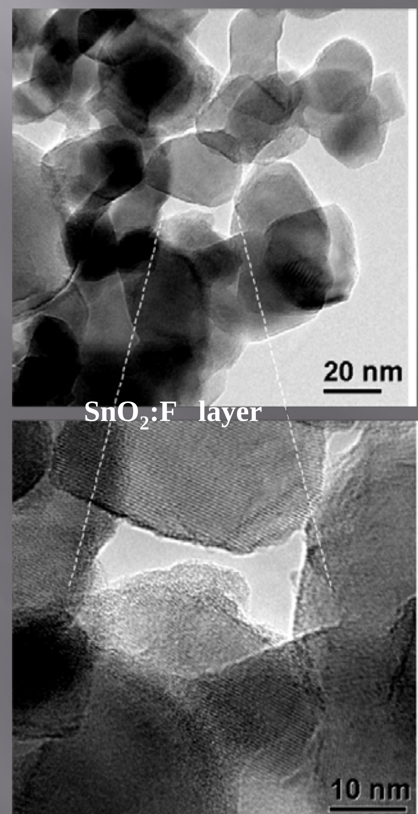
FTIR spectrum of the as-prepared film on silicon wafer rinsed multiple times with water and dried at 100°C.

No organics are detected (area of 1500-1000 cm^{-1})

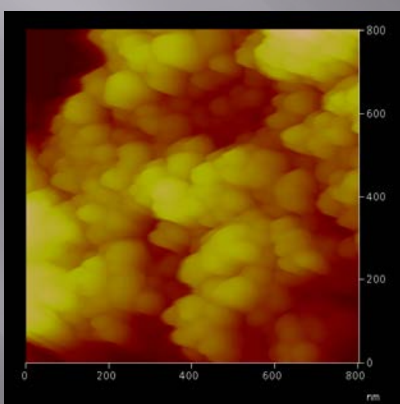


SEM image of the TiO_2 film on FTO glass prepared at room temperature

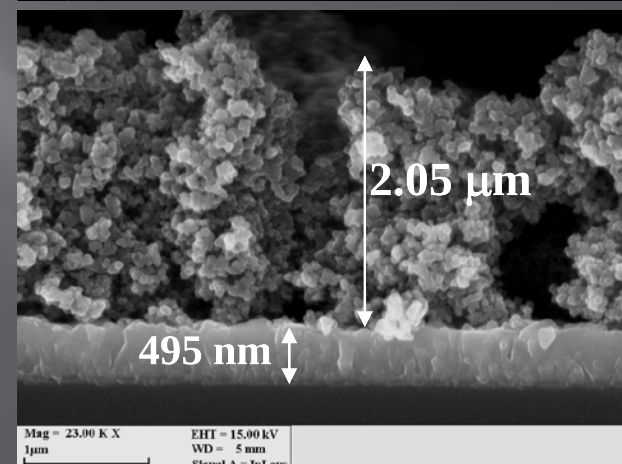




HR-TEM image of TiO_2 film

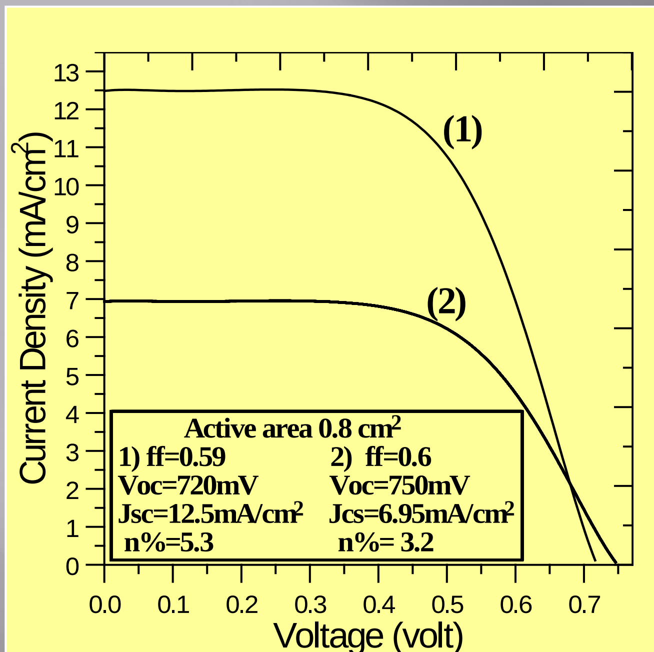


AFM image of the as-prepared TiO_2 film at room temperature



Cross-section SEM image of the as-prepared TiO_2 film.

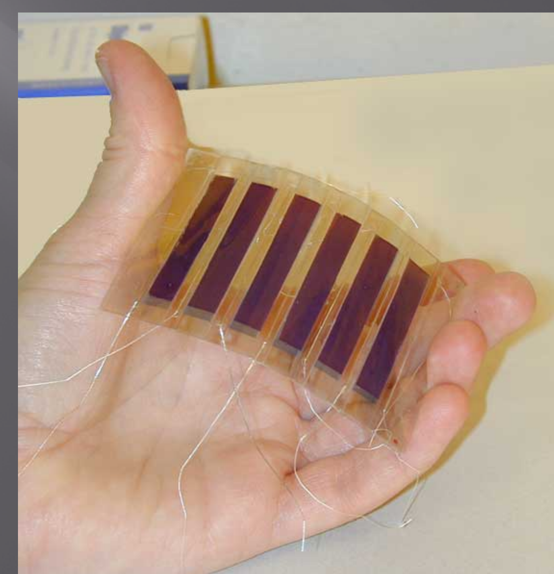
Substrate	TTIP (M)	TTIP: P25-TiO_2 (Molar ratio)	Q (%)	IPCE (%)	J_{sc} (mA/cm^2)	V_{oc} (mV)	*ff*	n (%)
FTO glass	0.180	0.14	0	31	6.9	673	0.58	2.7
	0.110	0.084	0	46	11.2	711	0.59	4.7
	0.070	0.056	0	58	11.7	720	0.59	5.0
	0.053	**0.042**	**0**	**62**	**12.5**	**720**	**0.59**	**5.3**
	0.035	0.028	2.5	59	9.7	700	0.60	4.1
	0.017	0.014	4.0	48	8.4	688	0.59	3.4
ITO-PET plastic	0.180	0.14	0	20	4.6	697	0.59	1.9
	0.110	0.084	0	27	5.9	736	0.59	2.6
	0.070	0.056	0	34	6.7	741	0.60	3.0
	0.053	**0.042**	**0**	**41**	**6.9**	**750**	**0.60**	**3.2**
	0.035	0.028	2.4	37	6.8	722	0.61	3.0
	0.017	0.014	5.3	32	5.5	694	0.60	2.3



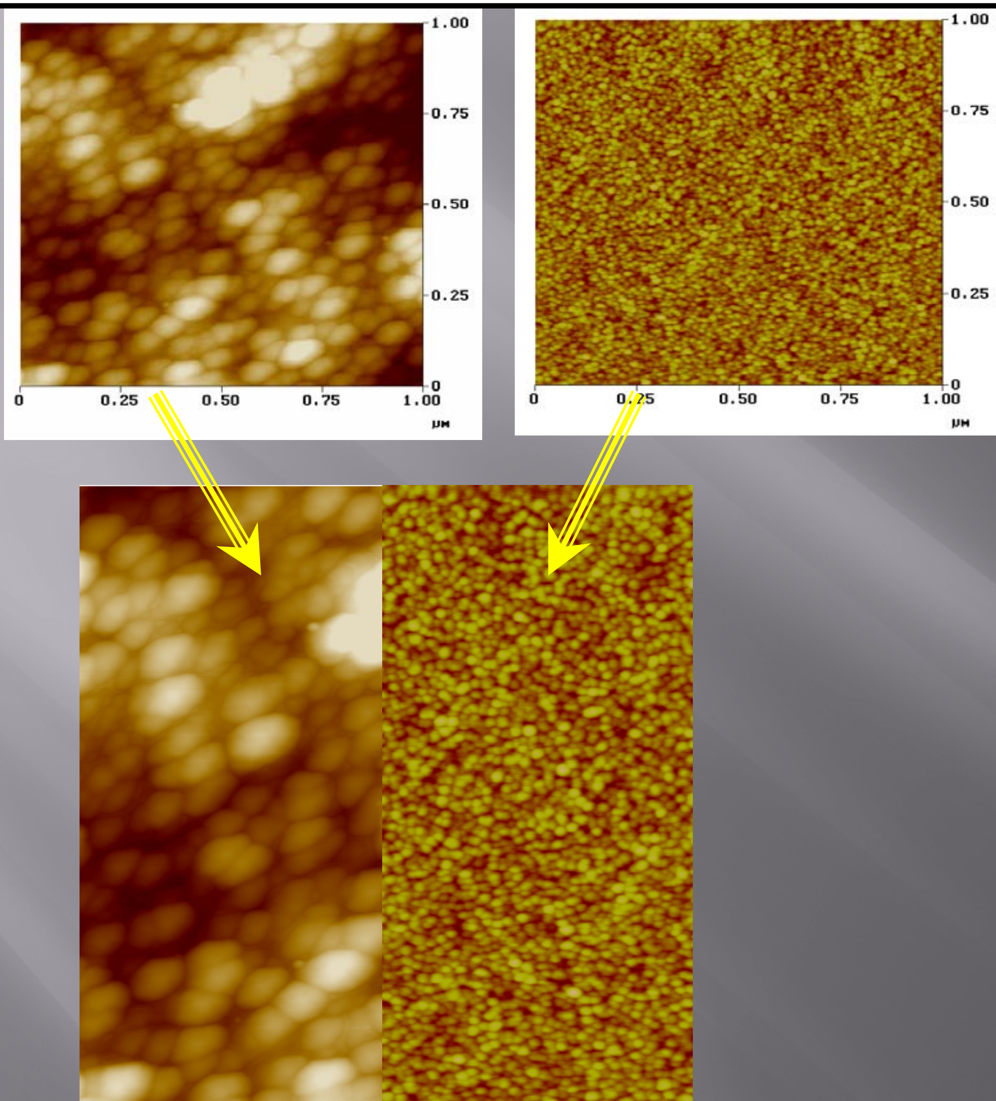
J-V curves at 1 sun for the DSSCs containing the as-prepared room temperature nanocrystalline TiO_2 film with quasi-solid state electrolyte employing:

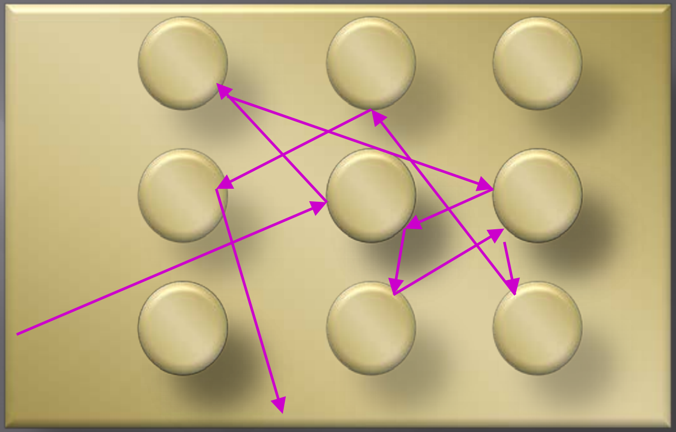
(1) FTO glass,

(2) ITO-PET plastic substrate.



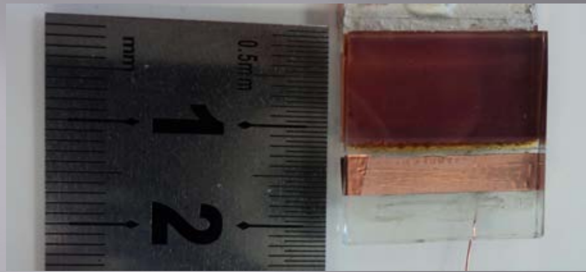
Light entrapment by multiple scattering

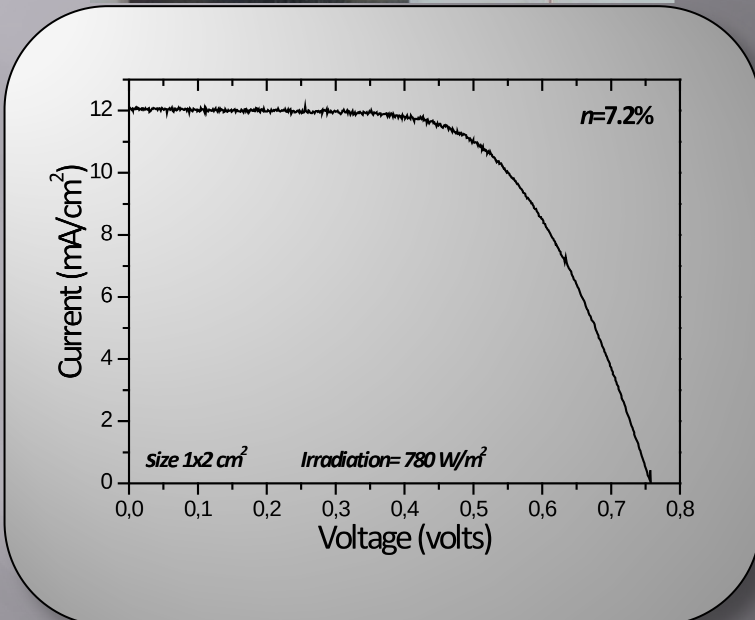


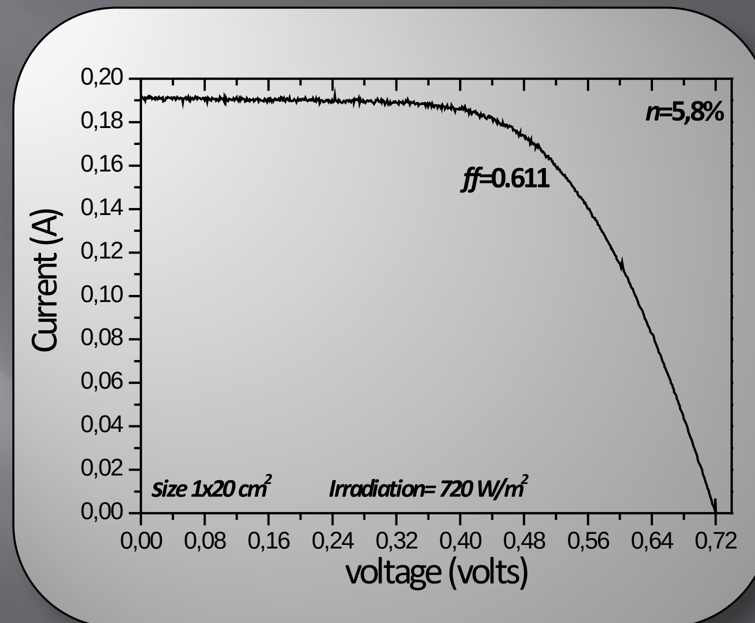


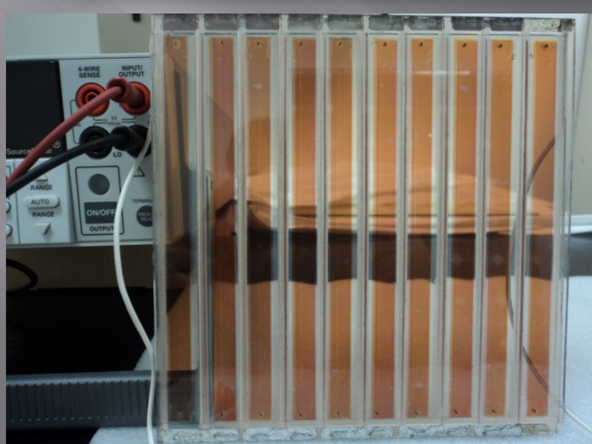
Which are the topics that are essential for reliable and cheap production technology?

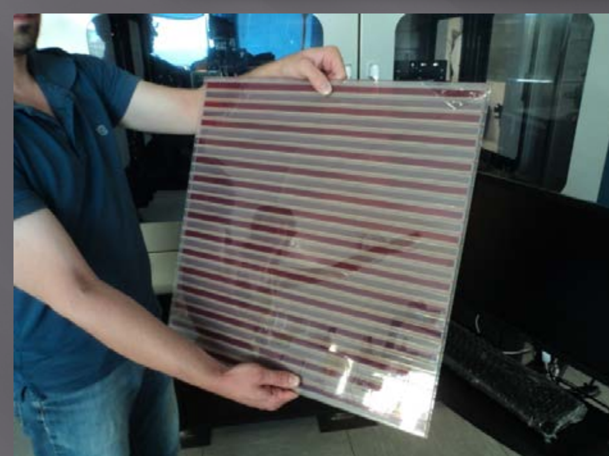
1. Large area deposition of uniform TiO_2 layers.
2. Development of methods for dye-staining and electrolyte filling
3. Internal electrical interconnection of individual cells
4. Sealing of modules
5. Long term stability
6. Evaluation of process steps in terms of costs.




Current (mA/cm²)
Voltage (volts)
n=7.2%
Size 1x2 cm²
Irradiation= 780 W/m²
0 2 4 6 8 10 12
0,0 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8

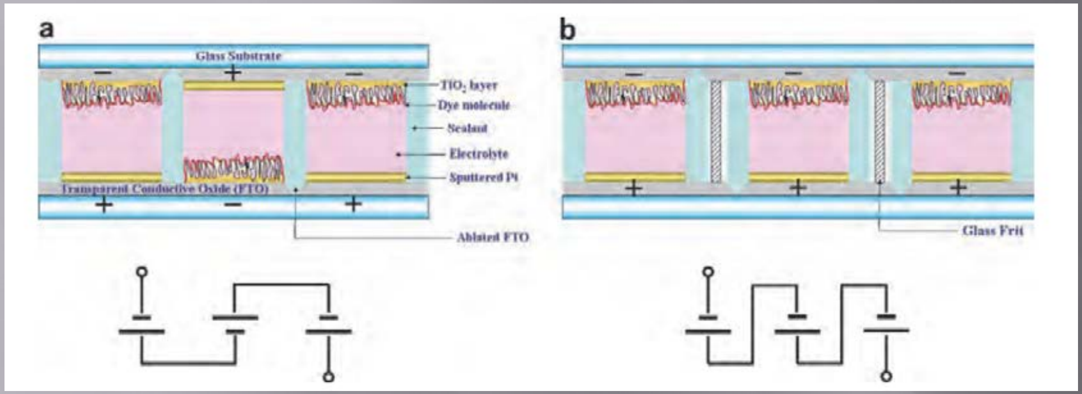

Current (A)
voltage (volts)
n=5,8%
ff=0.611
Size 1x20 cm²
Irradiation= 720 W/m²
0,00 0,02 0,04 0,06 0,08 0,10 0,12 0,14 0,16 0,18 0,20
0,00 0,08 0,16 0,24 0,32 0,40 0,48 0,56 0,64 0,72

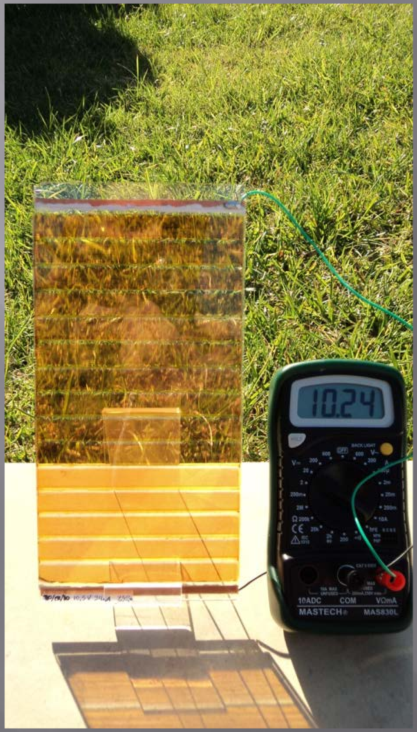




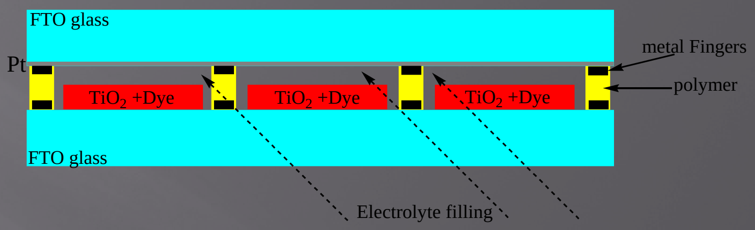
Type of cell connections

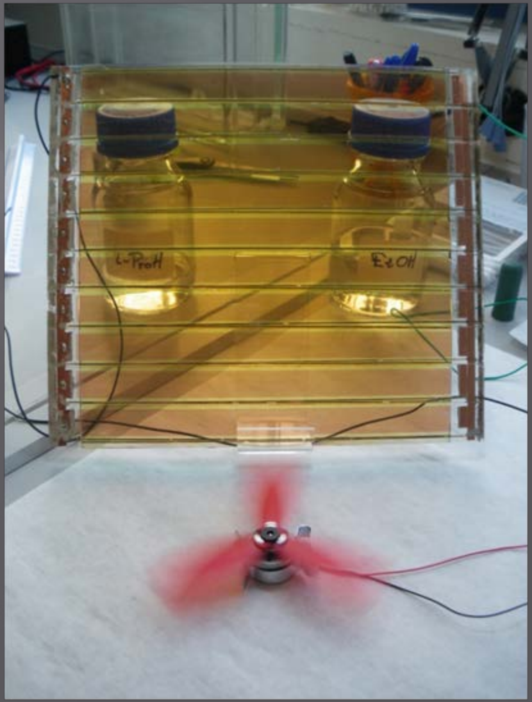
(1) In series

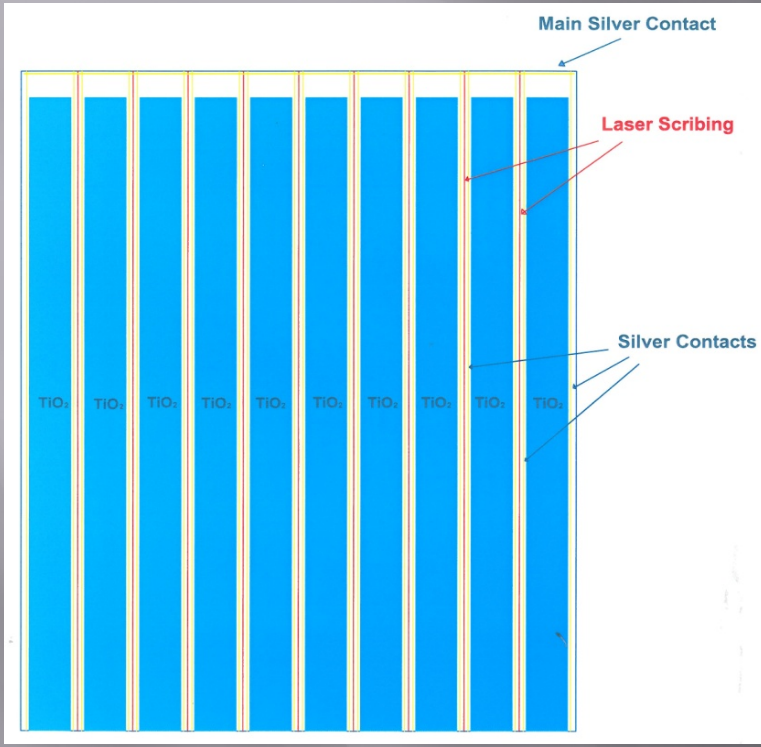




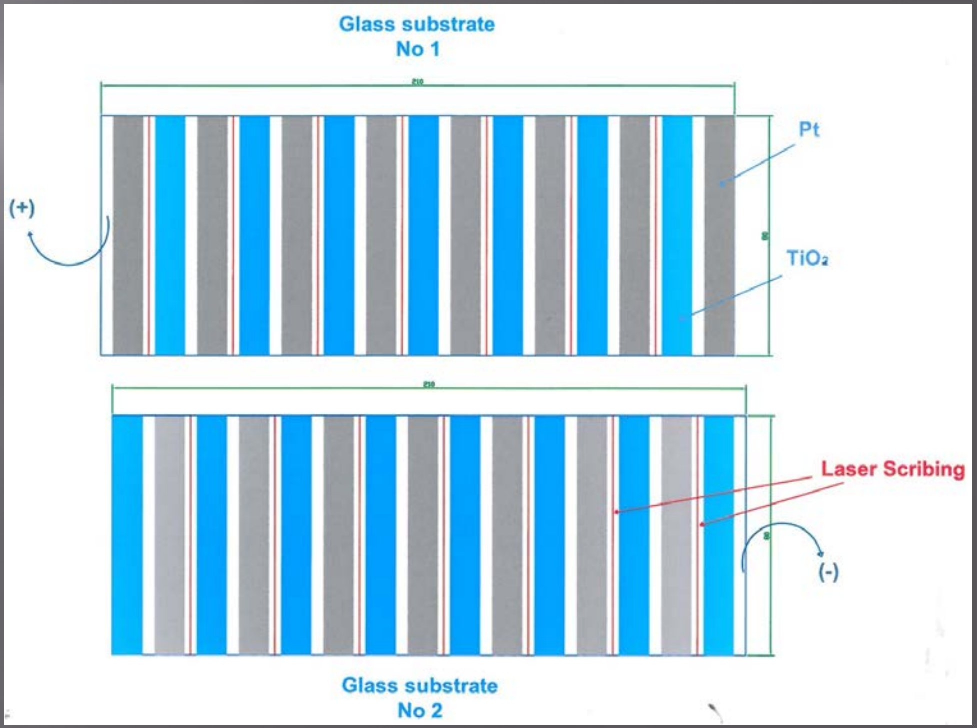
(2) in parallel



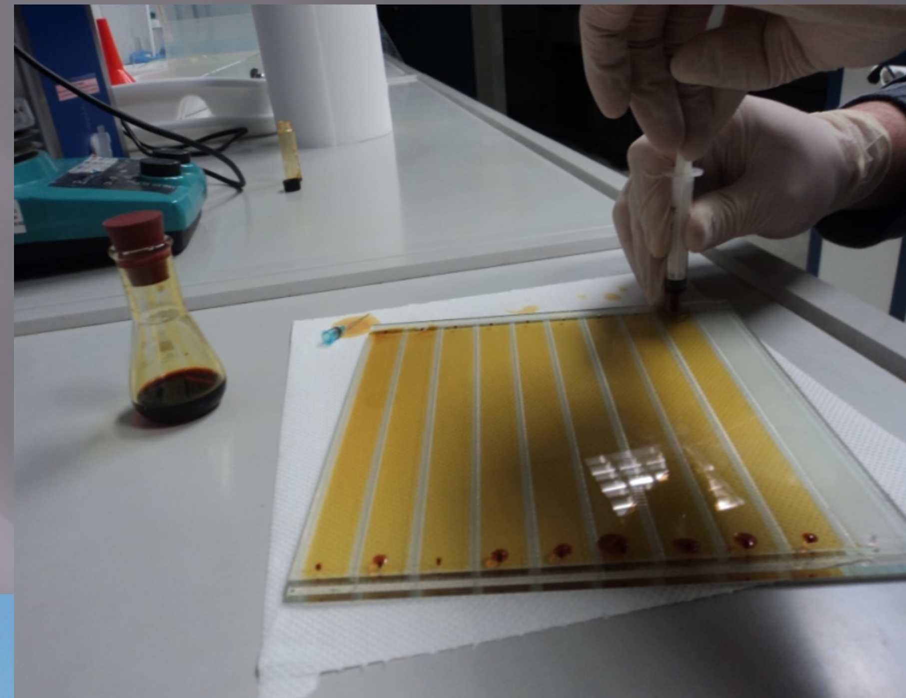


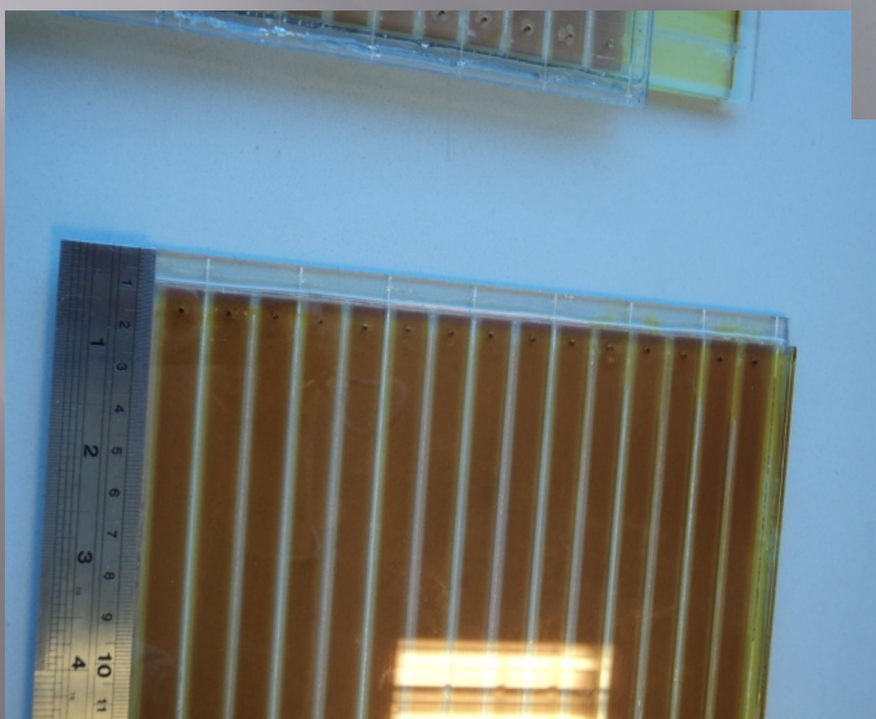


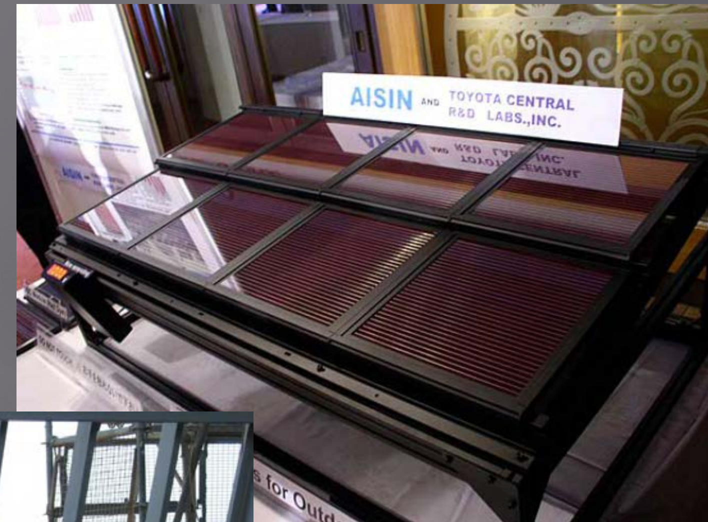
Main Silver Contact
Laser Scribing
Silver Contacts
TiO2
TiO2
TiO2
TiO2
TiO2
TiO2
TiO2
TiO2
TiO2
TiO2

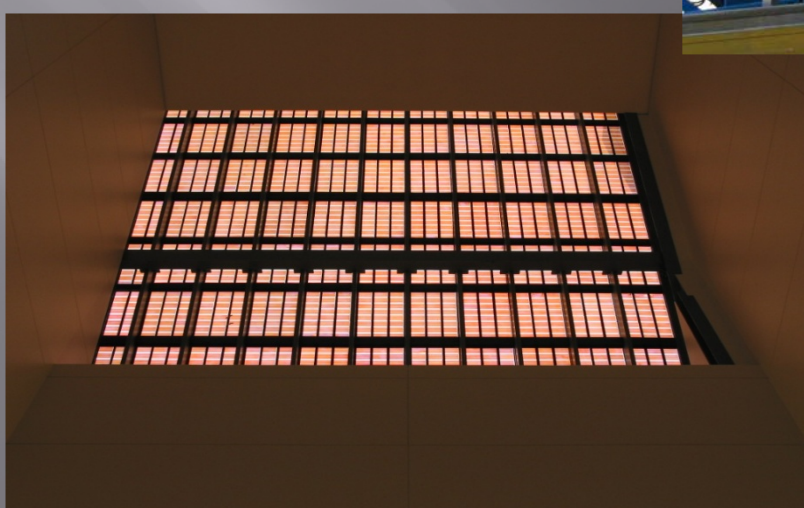


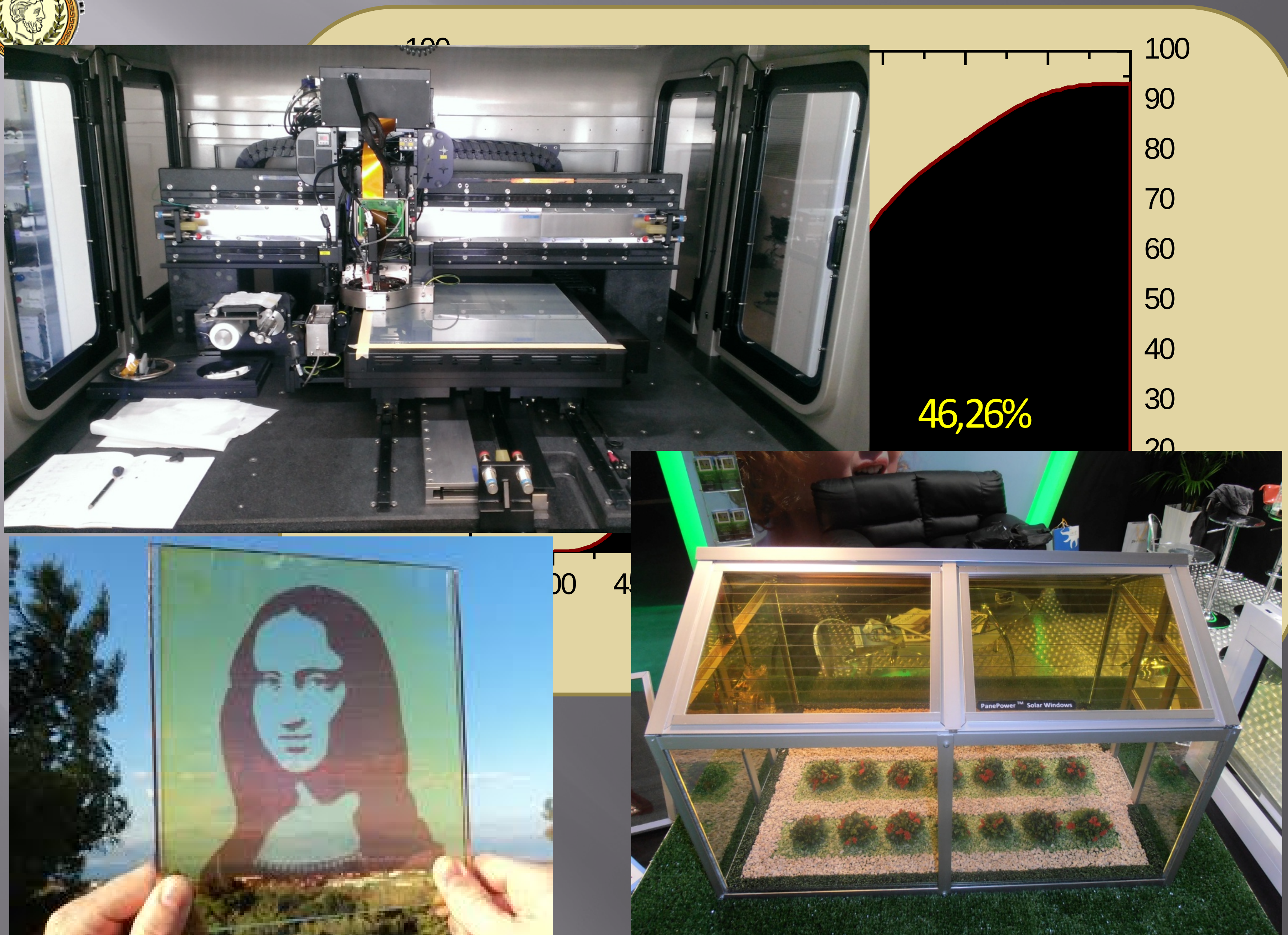
Glass substrate
No 1
Pt
(+)
TiO2
Laser Scribing
(-)
Glass substrate
No 2

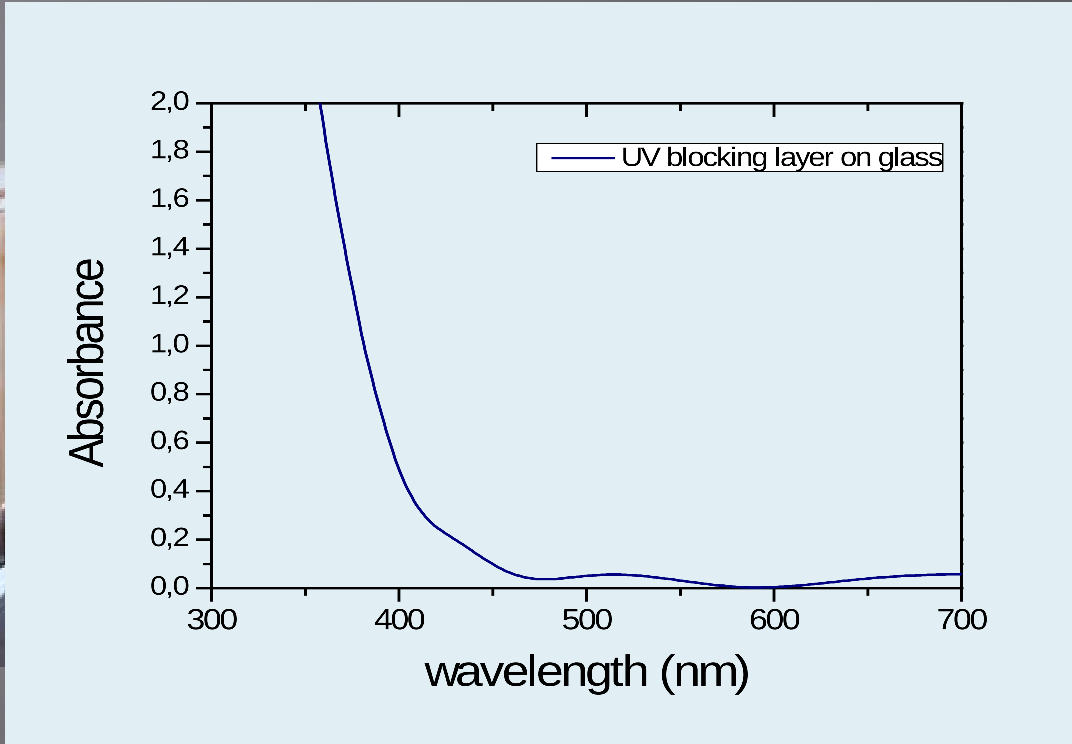





AISIN AND TOYOTA CENTRAL
R&D LABS.,INC.

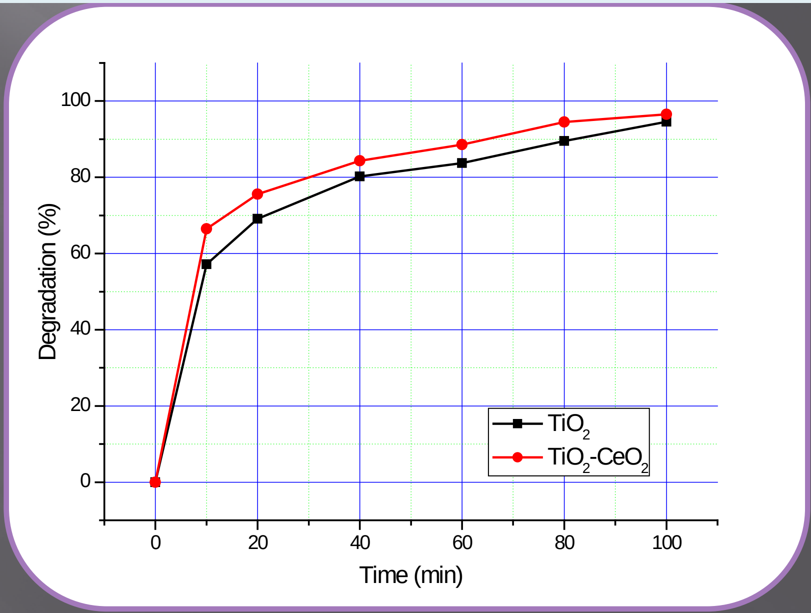


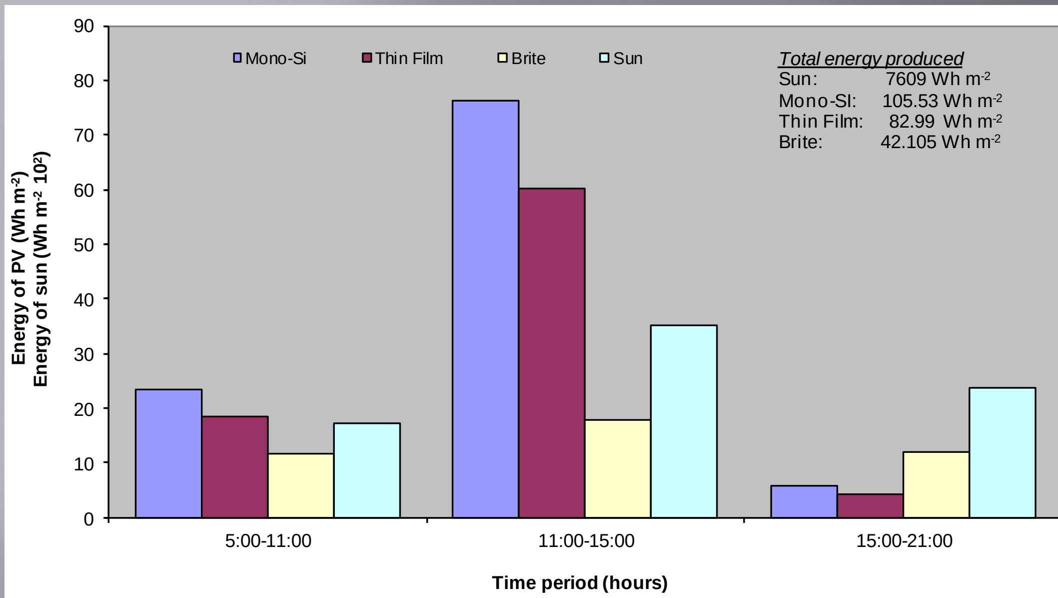

100
90
80
70
60
50
40
30
46,26%
PanePower™ Solar Windows

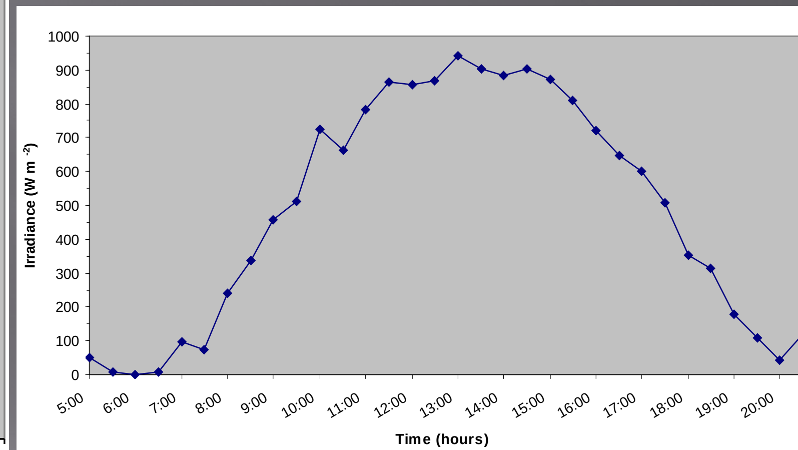


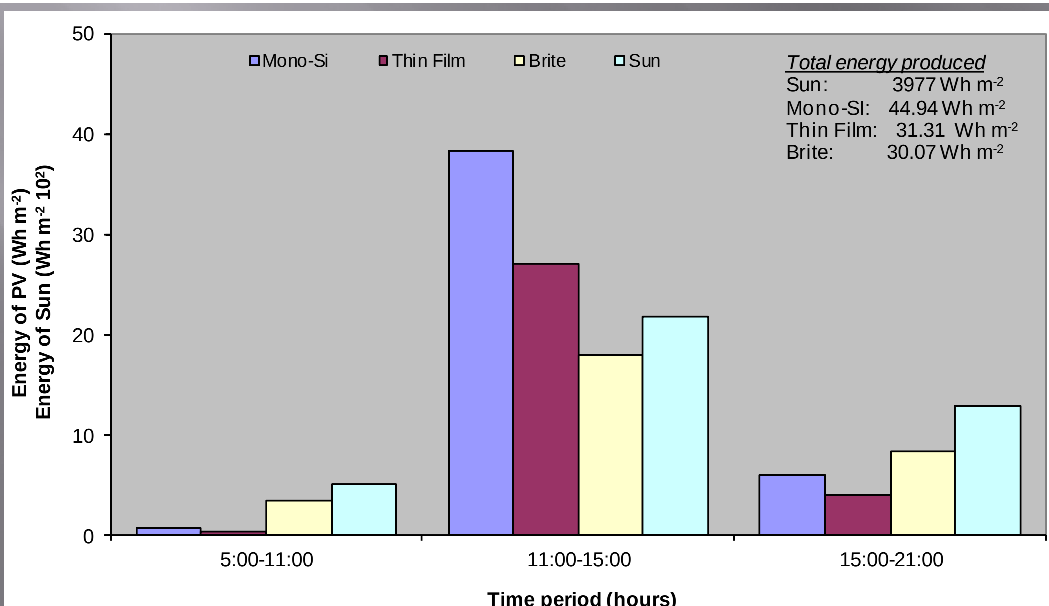
UV transmittance 1.4%

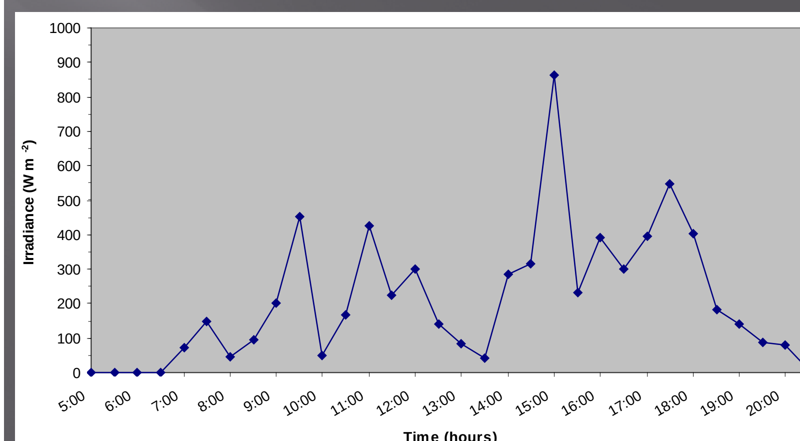
ΔJsc<5%, ΔVoc<2%

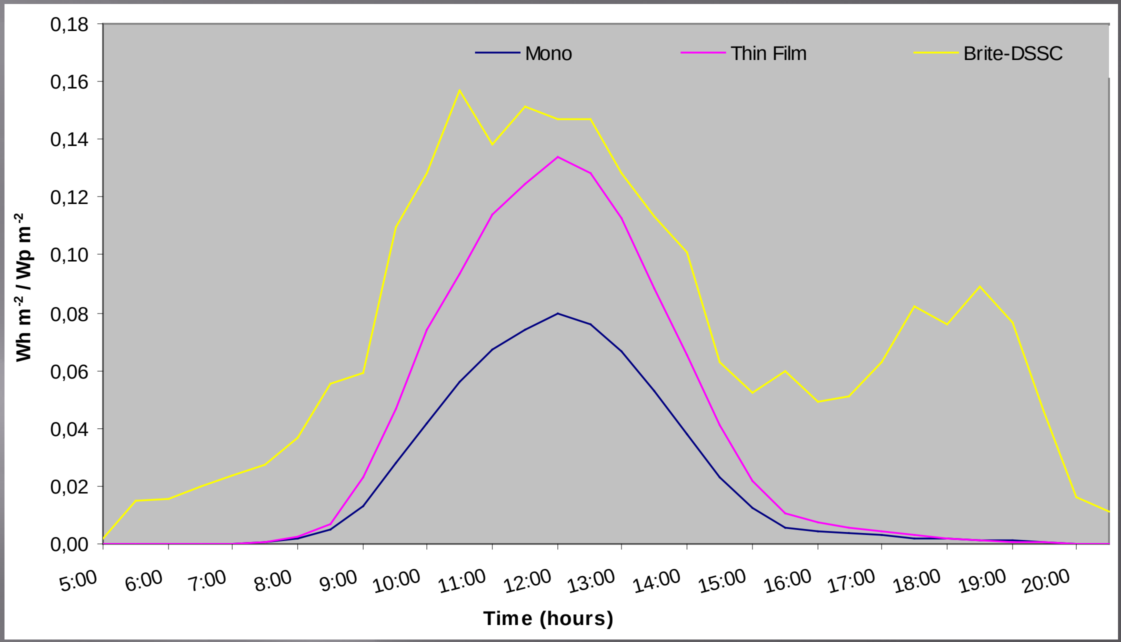


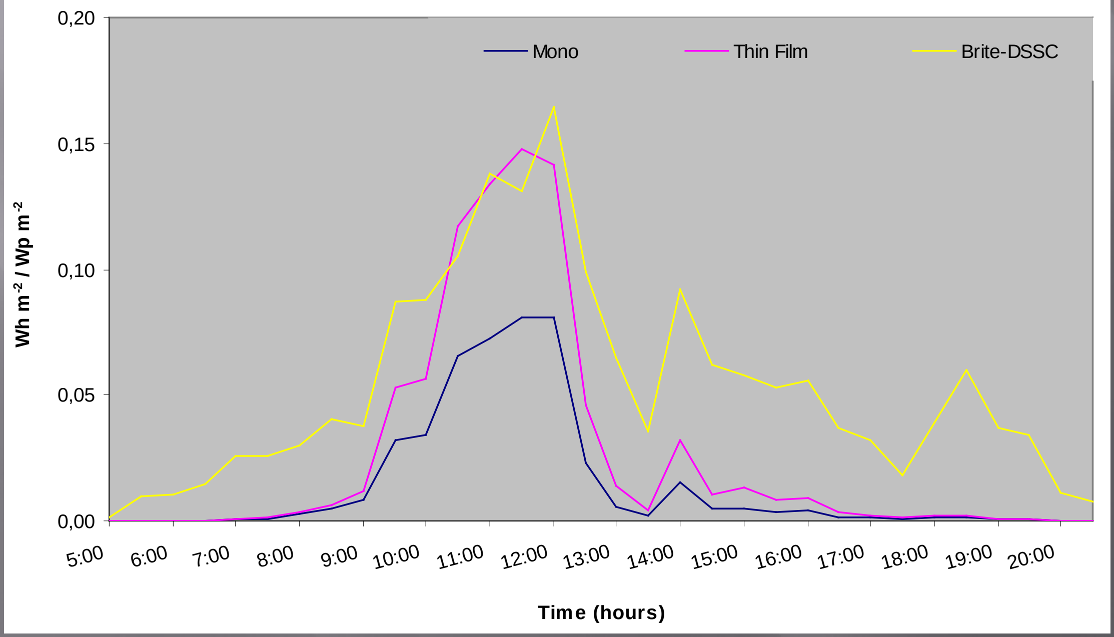

Mono-Si
Thin Film
Brite
Sun
Total energy produced
Sun: 7609 Wh m-2
Mono-SI: 105.53 Wh m-2
Thin Film: 82.99 Wh m-2
Brite: 42.105 Wh m-2
Energy of PV (Wh m-2)
Energy of sun (Wh m-2 10^2)
5:00-11:00
11:00-15:00
15:00-21:00
Time period (hours)

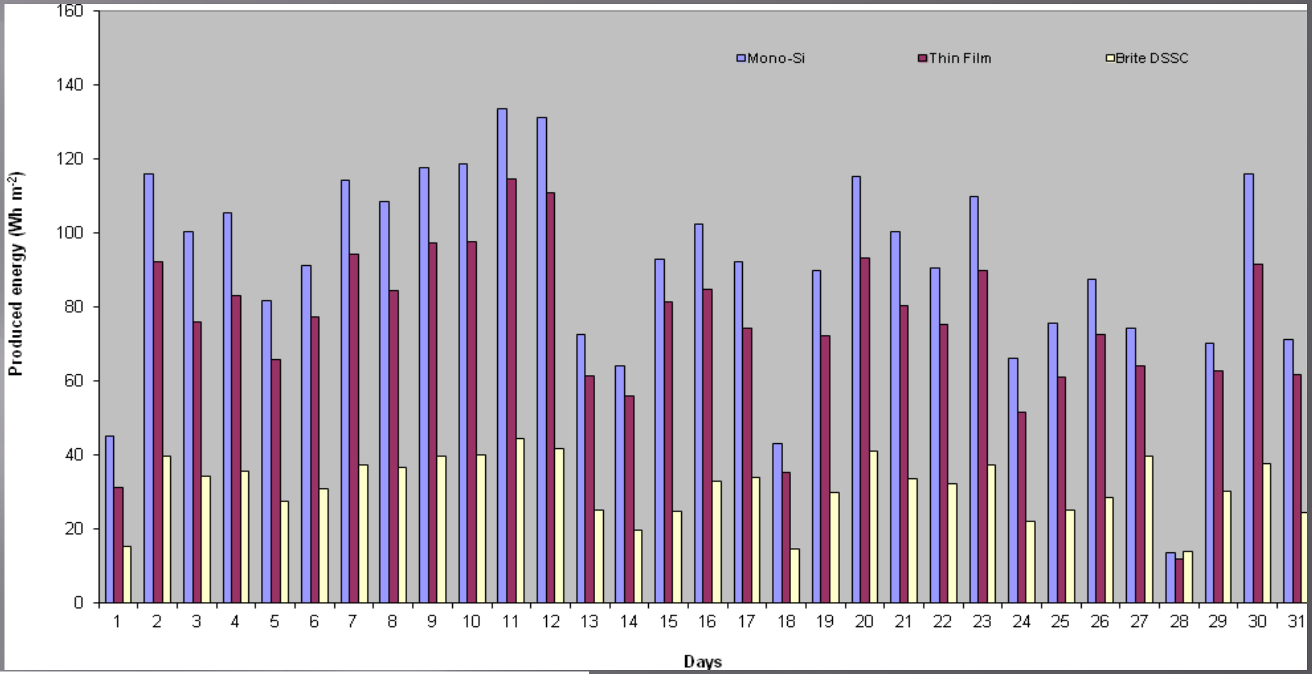

Irradiance (W m -2)
Time (hours)

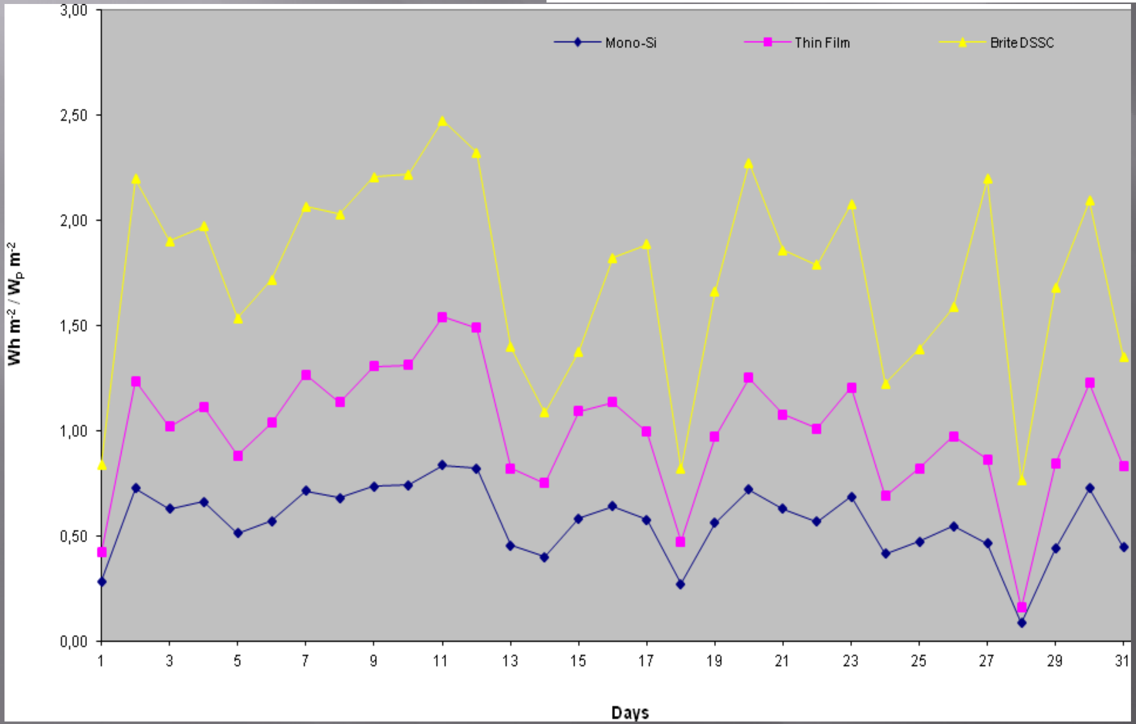

Mono-Si
Thin Film
Brite
Sun
Total energy produced
Sun: 3977 Wh m-2
Mono-SI: 44.94 Wh m-2
Thin Film: 31.31 Wh m-2
Brite: 30.07 Wh m-2
Energy of PV (Wh m-2)
Energy of Sun (Wh m-2 10^2)
5:00-11:00
11:00-15:00
15:00-21:00
Time period (hours)

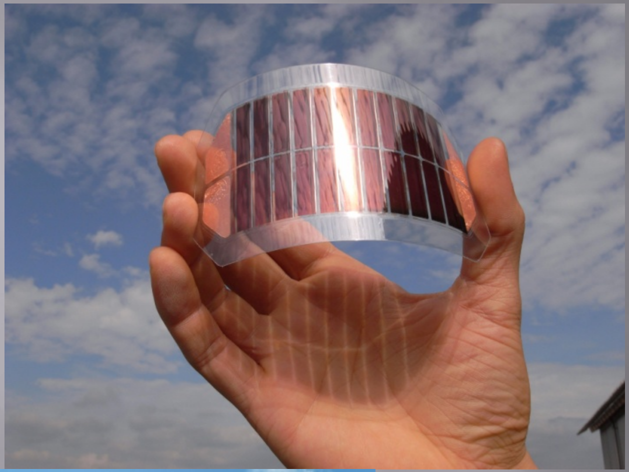

Irradiance (W m -2)
Time (hours)

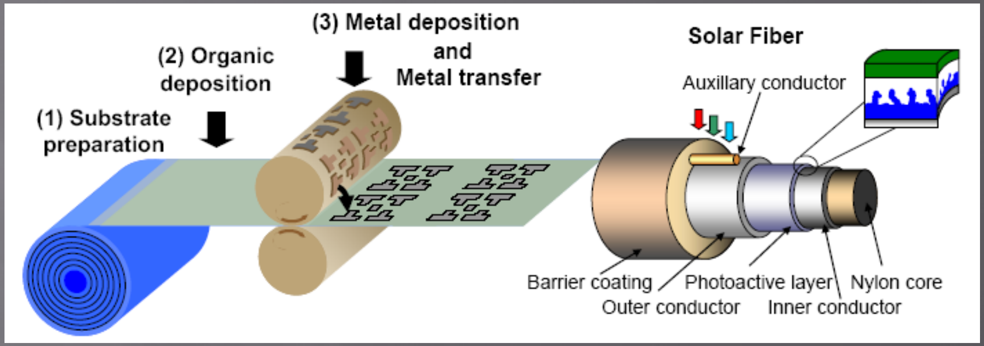

Mono
Thin Film
Brite-DSSC
Wh m-2 / Wp m-2
Time (hours)
0,00
0,02
0,04
0,06
0,08
0,10
0,12
0,14
0,16
0,18
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00


Mono
Thin Film
Brite-DSSC
Wh m-2 / Wp m-2
Time (hours)
0,00
0,05
0,10
0,15
0,20
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00


Mono-Si
Thin Film
Brite DSSC
Produced energy (Wh m-2)
Days

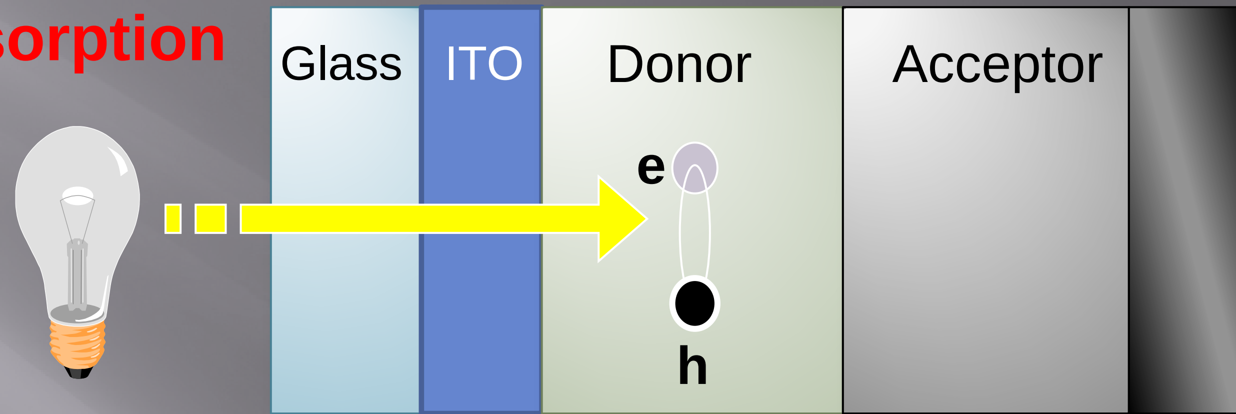

Mono-Si
Thin Film
Brite DSSC
Wh m-2 / Wp m-2
Days




(1) Substrate preparation
(2) Organic deposition
(3) Metal deposition and Metal transfer
Solar Fiber
Auxillary conductor
Barrier coating
Outer conductor
Photoactive layer
Inner conductor
Nylon core

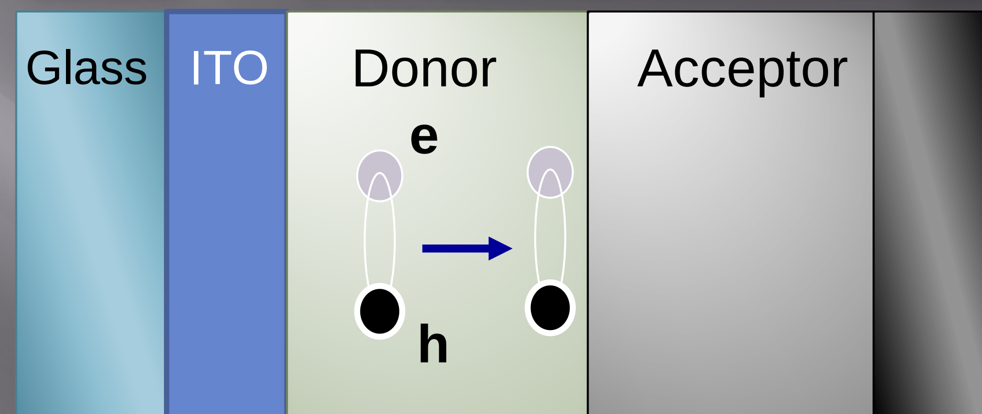

POWER PLASTIC
KONARKA

Absorption

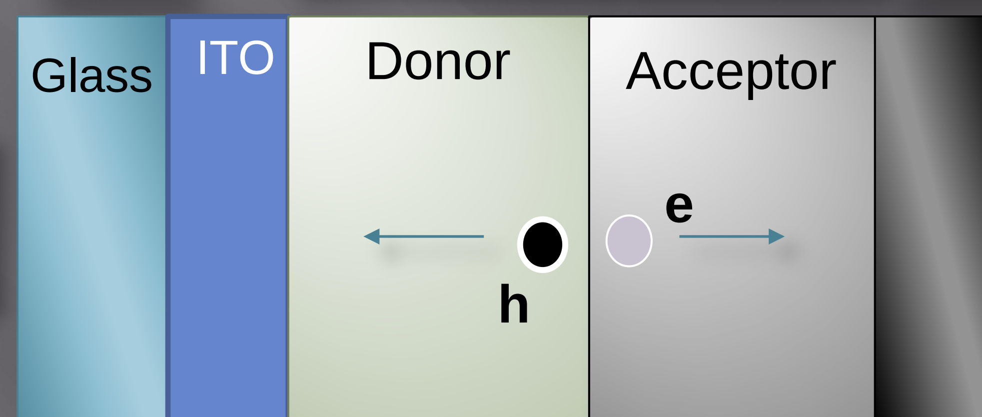


Energy Migration

Diffusion length ~ 10 nm !!!!

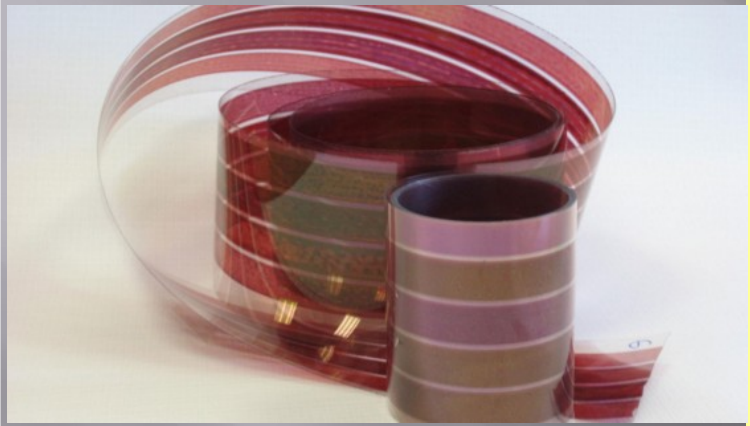


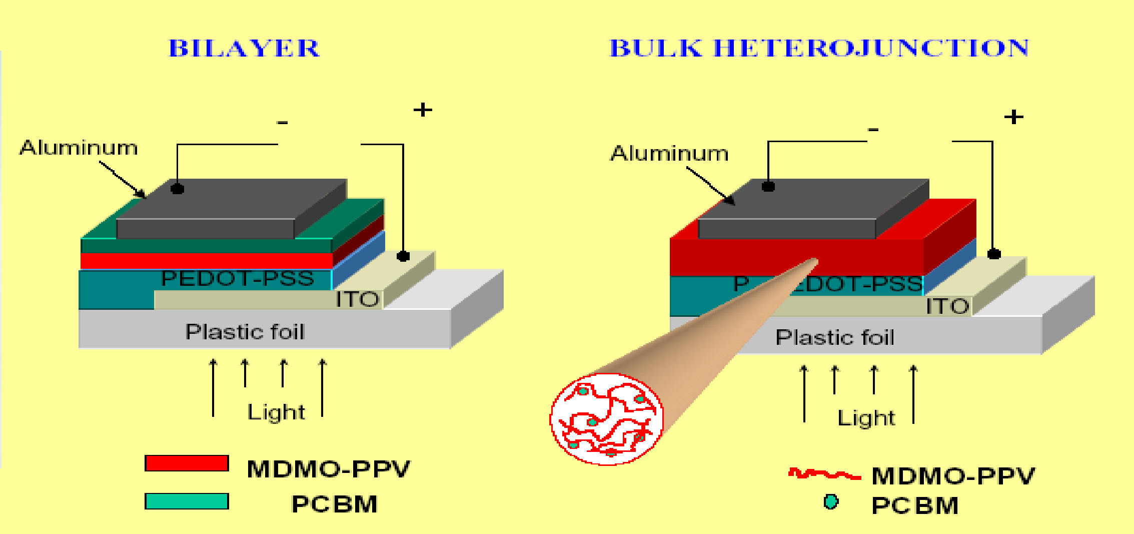
Photoinduced Charge Generation



Critical Steps in organic Photovoltaics

1. Photon Absorption (Band gaps, e.g. 1.3-2.0 eV on earth).
2. Exciton Diffusion (D/A interface within 10-70nm).
3. Charge separation (orbital offsets)
4. Charge transportation (morphology)
5. Charge collection at electrodes.





Key Loses of OPVs

1. Photon loss (light wavelength/spectra vs Band Gap)
2. Exciton Loss (D/A domain size/morphology/Energy Levels)
3. Carrier Loss (Transport Pathway/Morphology/ Molecular Packing/Collection at Electrodes).

Thanks for your attention