Mesoscopic Injection Solar Cells for Electricity Generation from Sunlight

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Industrial Partners,

Humanity's Top Ten Problems for next 50 years

1. ENERGY
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

2003	6.3	Billion People
2050	8-10	Billion People

Source Richard Smalley Energy & Nanotechnology Conference
Rice University, Houston May 3, 2003

THE SOLAR CHALLENGE

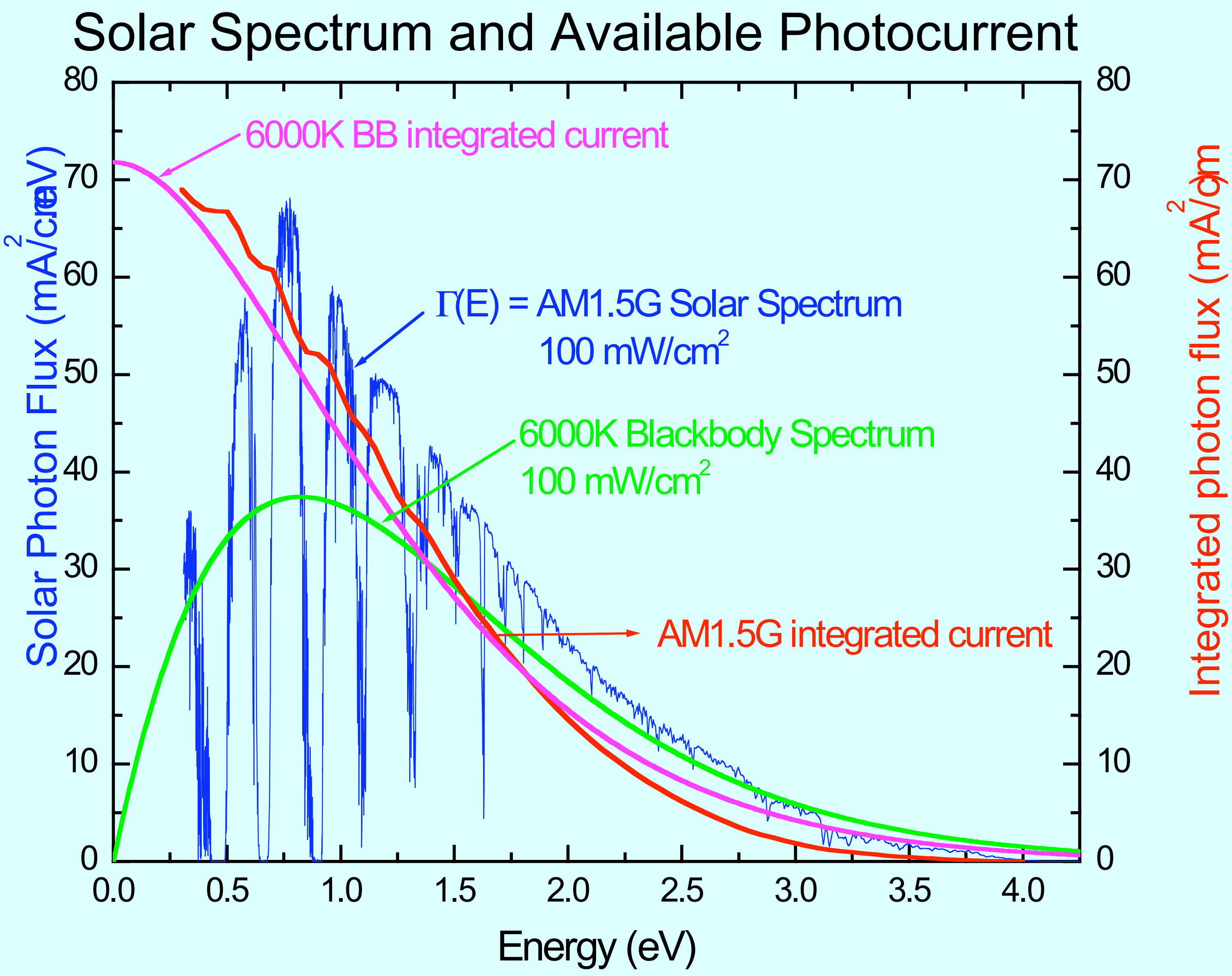
- With a projected global population of 12 billion by 2050 coupled with moderate economic growth, the total global energy consumption is estimated to be ~28 TW. Current global use is ~11 TW.

- To cap CO_2 at 550 ppm (twice the pre-industrial level), most of this additional energy needs to come from carbon-free sources.

- Solar energy is the largest non-carbon-based energy source (100,000 TW).

- However, it has to be converted at reasonably low cost.

THE SOLAR RESOURCE

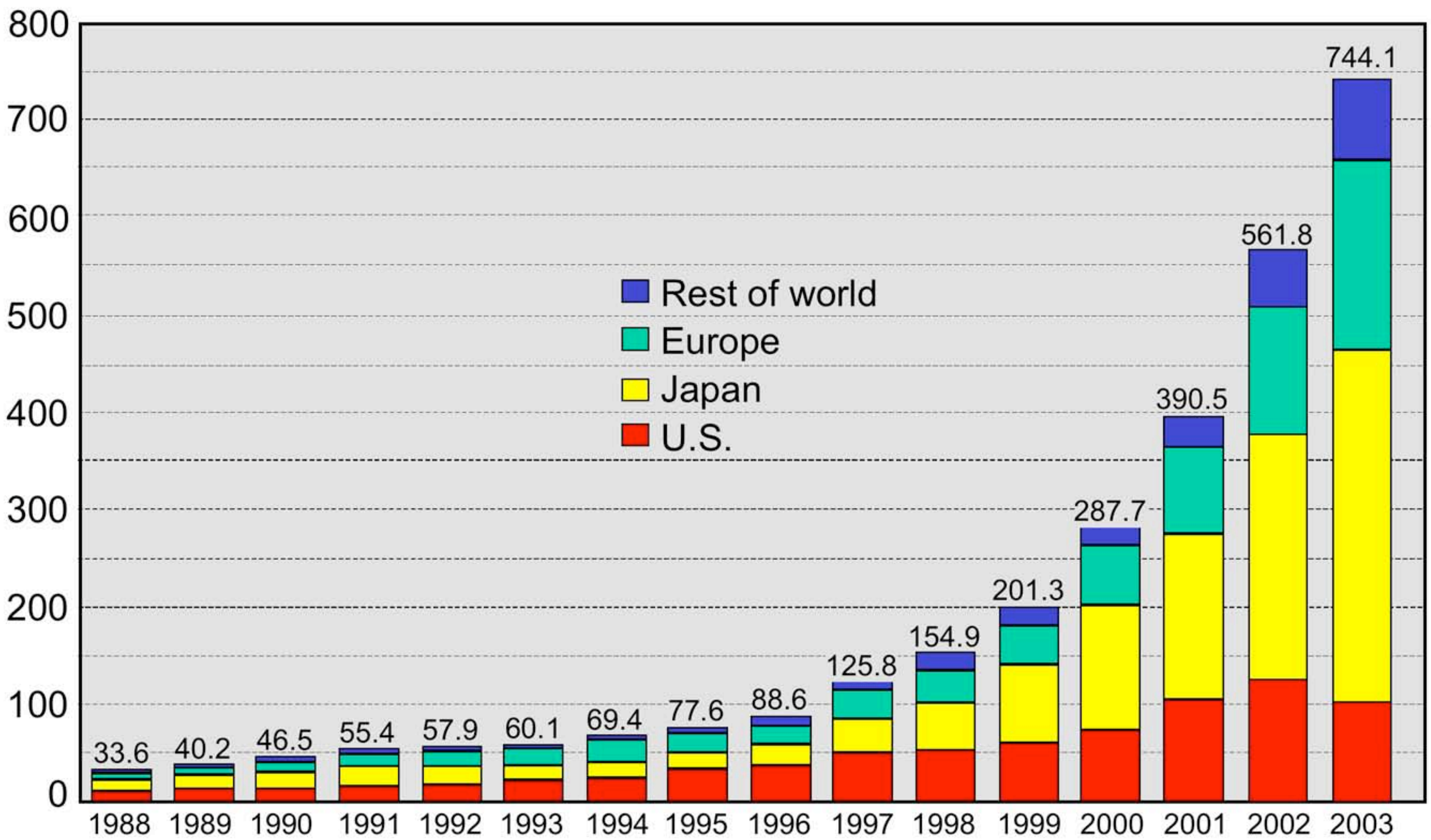


Photovoltaic Cells

I. **1st Generation**
   - **Single crystal Si**
   - **Poly-grain Si**

II. **2nd Generation (Low Cost--Mainly Thin Films)**
   - **Amorphous Si**
   - **Thin film Si**
   - **$CuInSe_2$**
   - **CdTe**
   - **Dye-sensitized Photochemical Cell**
   - **Organic PV (molecular and polymeric)**

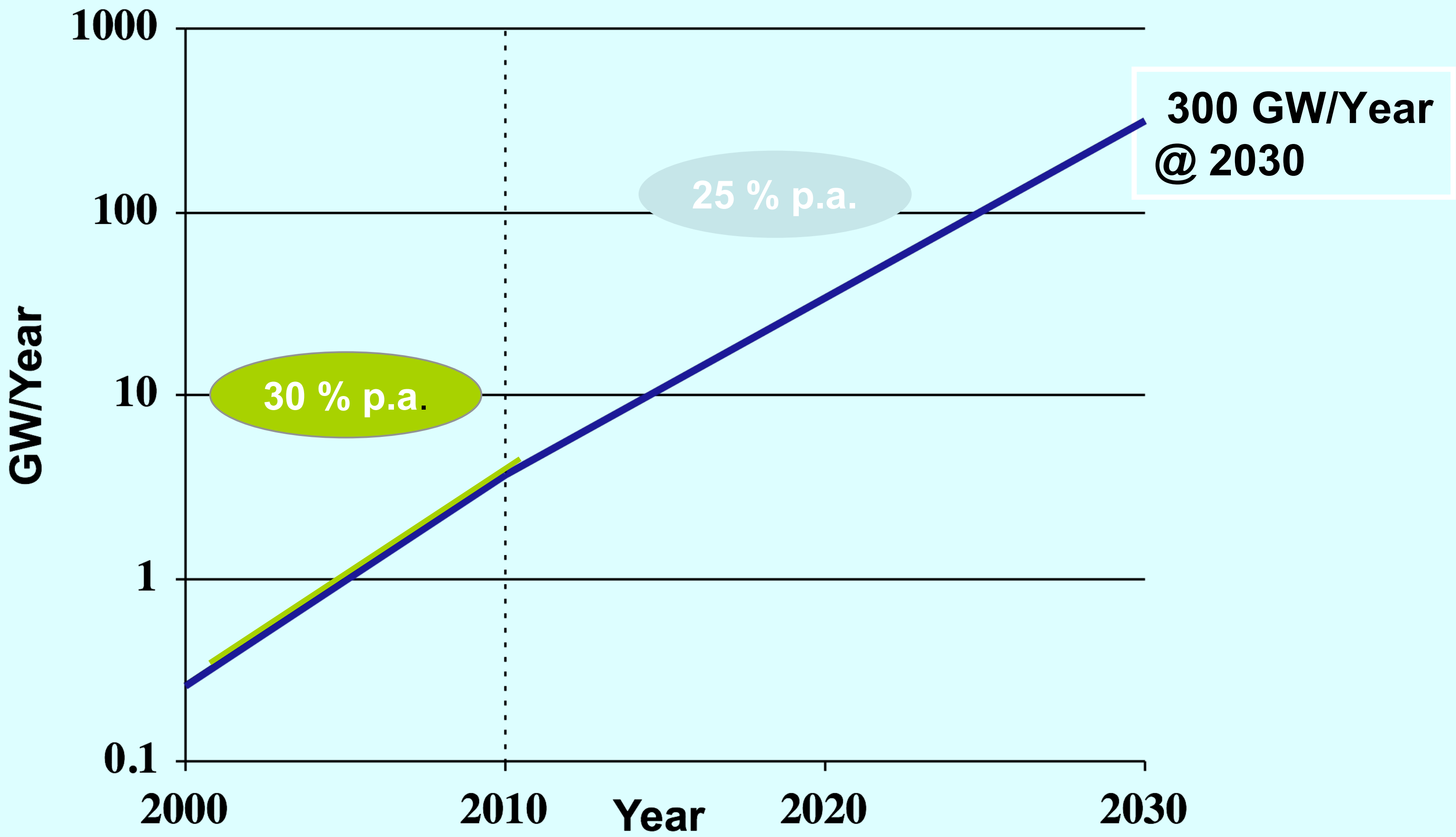
III. **3rd Generation (n_{theor}>31%(the Queisser-Shockley limit))**
   - ***(High efficiency multi-gap tandem cells (already here))***
   - **Hot electron converters**
   - **Carrier Multiplication cells**
   - **Mid-band PV**
   - **Quantum Dot Solar Cells**
   - **Other approaches**



Source: *PV News*, March 2004

World PV Cell/Module Production (in MW)

Photovoltaic market growth projection until 2030

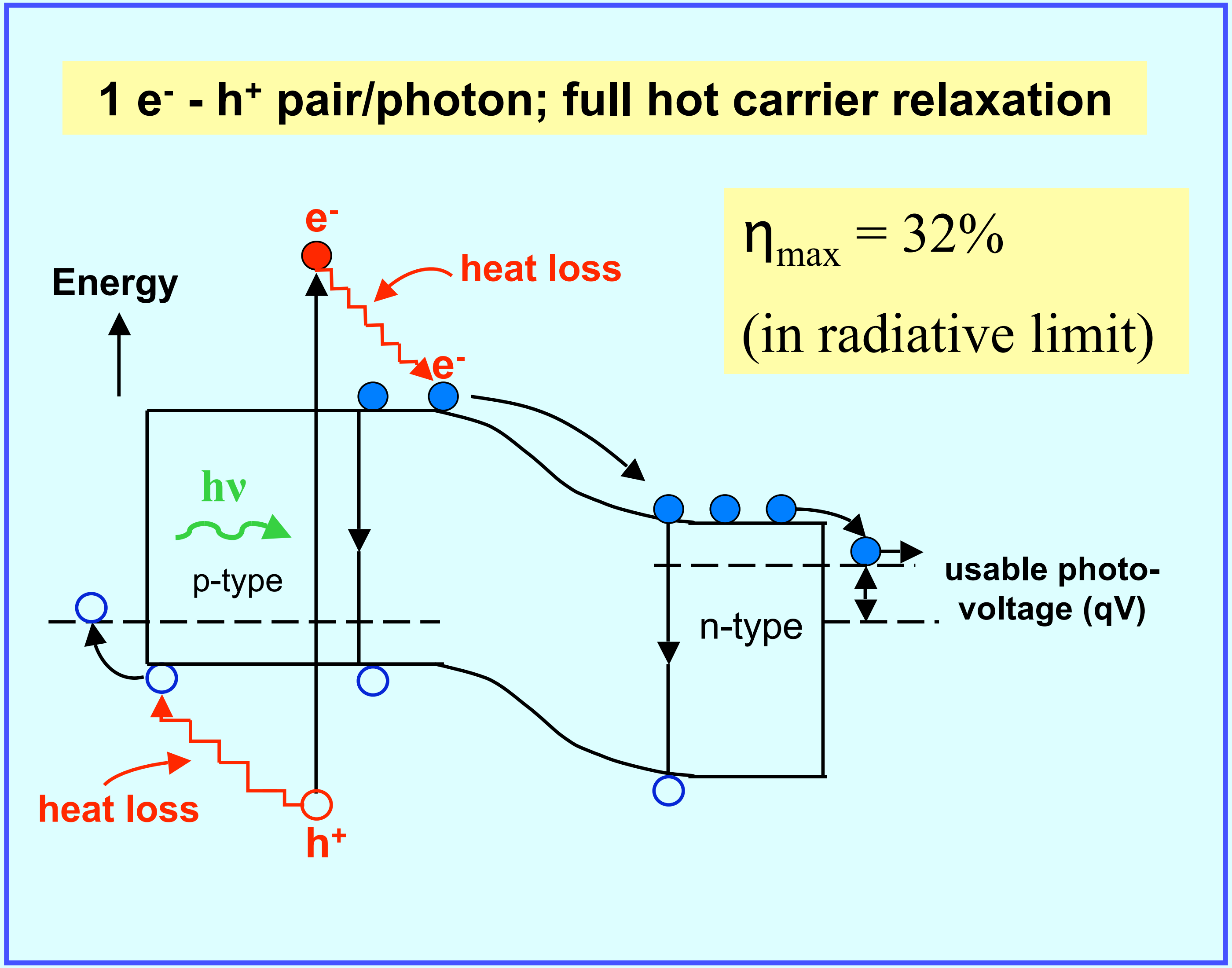


Courtesy Dr. Winfried Hoffman, CEO, RWE, SCHOTT Solar GmbH

PRESENT PV TECHNOLOGY

(Dominated by semiconductor p-n junctions)

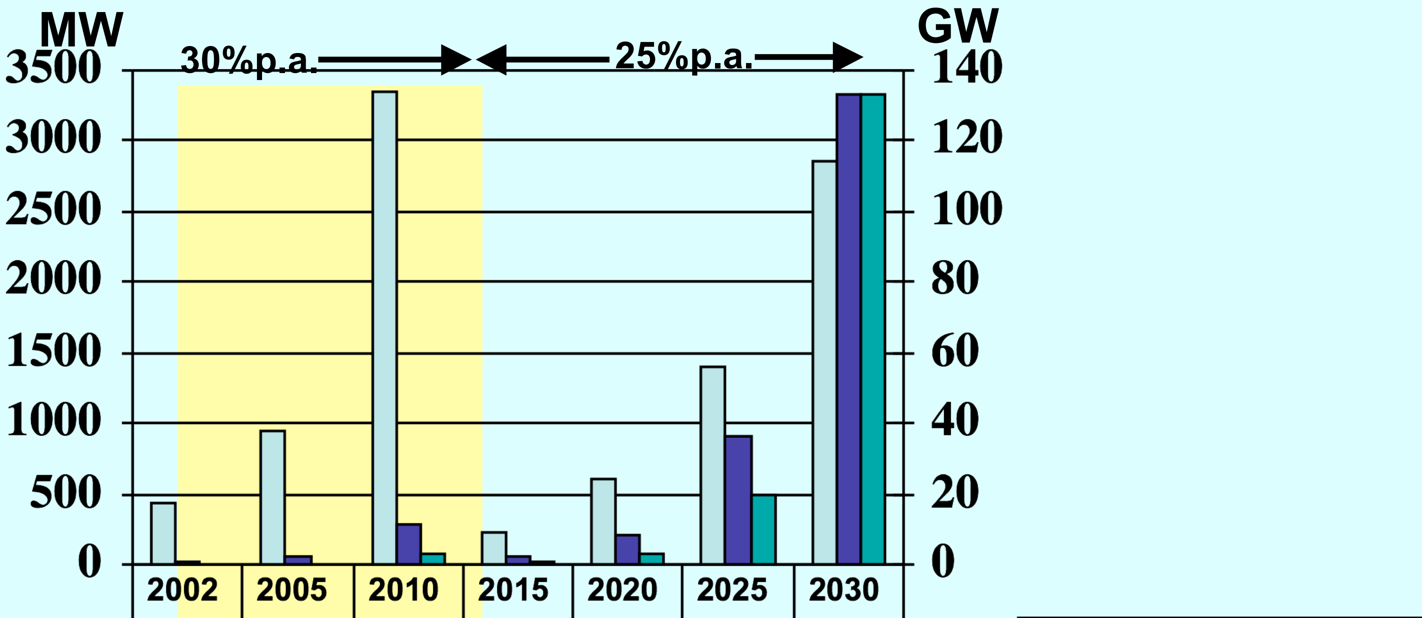
Conventional Single Homojunction PV Cell



Production Forecast of Solar Modules Using Different Technologies

2010 (Forecast)

Jp	1.200
EU	1.000
US	500
SOA	500
ROW	500
Σ	3.700

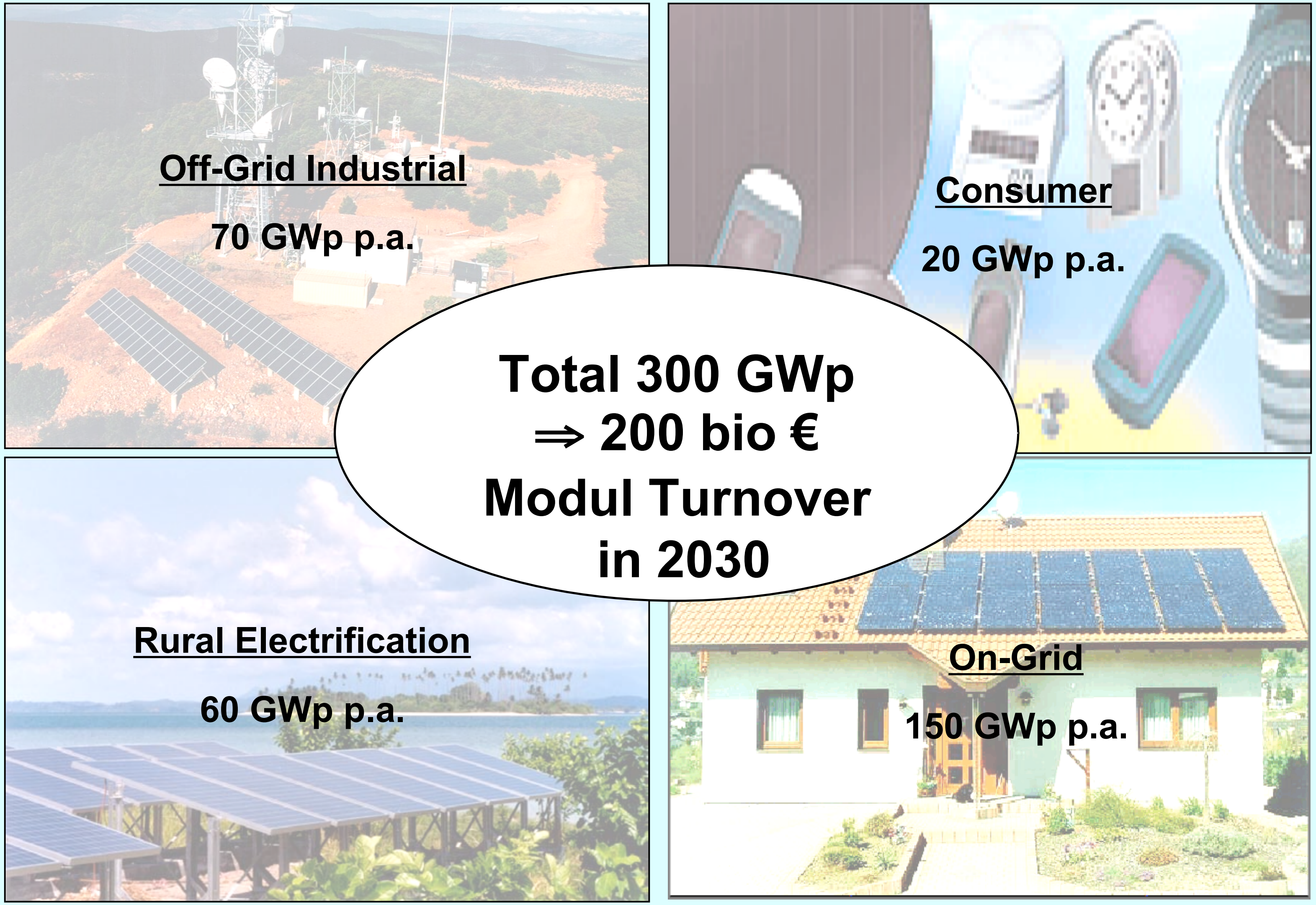


	2002	2005	2010	2015	2020	2025	2030
c-Si	430	950	3340				
thin film	20	50	290				
"New Concepts"			70				
c-Si				9	24	56	114
thin film				2	8	36	133
"New Concepts"				1	3	20	133

Courtesy Dr. Winfried Hoffman, CEO, RWE, SCHOTT Solar GmbH

Market Size in 2030 for the four market segments

Courtesy Dr. Winfried Hoffman, CEO, RWE, SCHOTT Solar GmbH



Emerging and new applications call for:

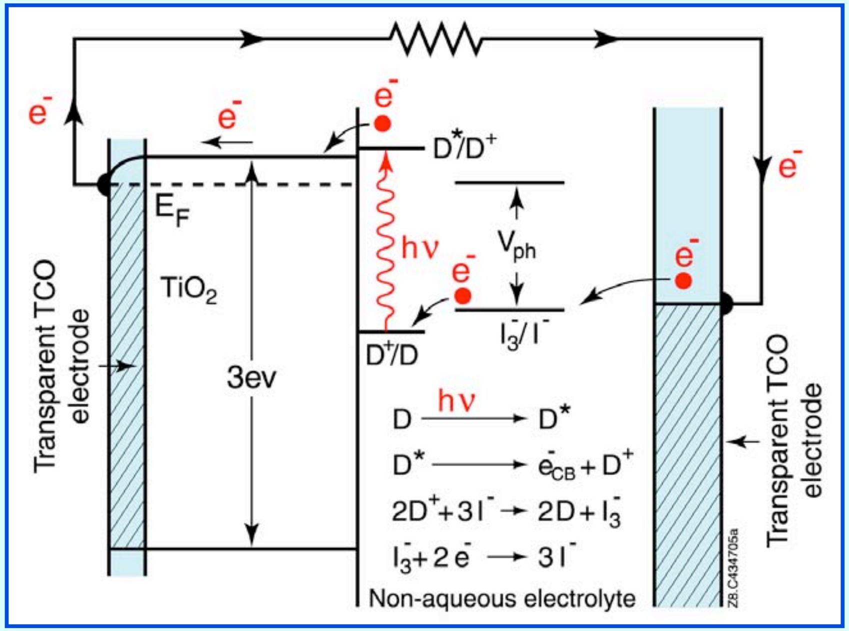
- colour
- flexibility
- light weight
- easy of integration
- many more

... further development and new technologies in order to meet optimally the customer demands and needs

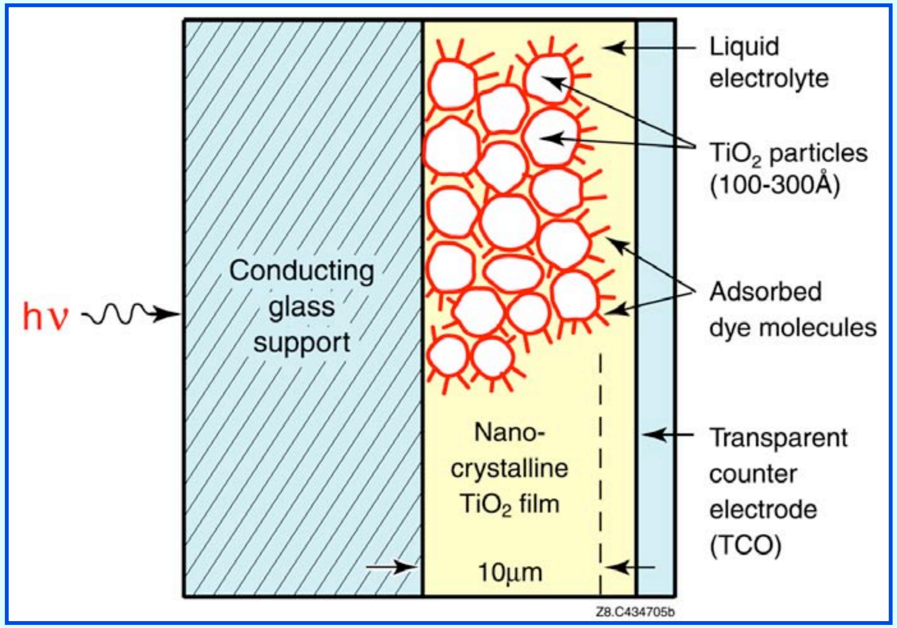
Courtesy Dr. Winfried Hoffman, CEO, RWE, SCHOTT Solar GmbH

Mesoscopic Injection Solar Cells

Band Diagram

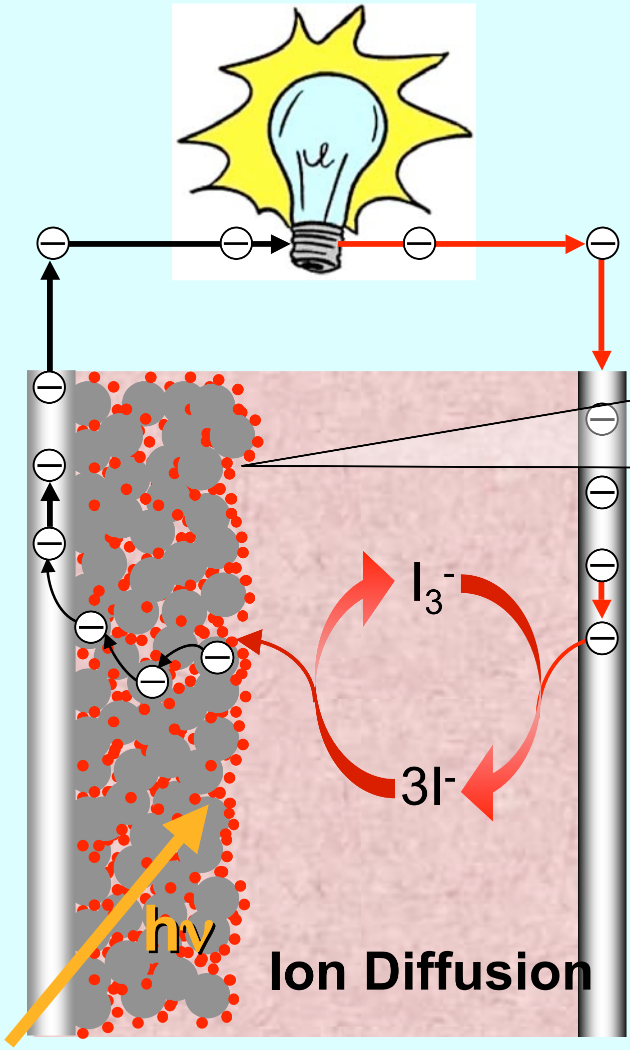


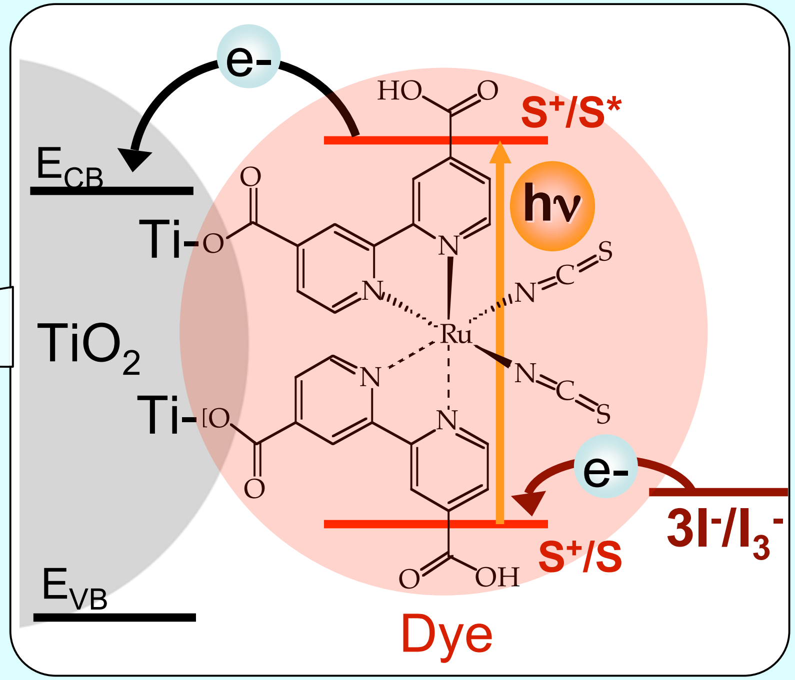
Scheme



M. Grätzel, Nature 2001, 414, 338–344

Sensitized mesoscopic heterojuntions

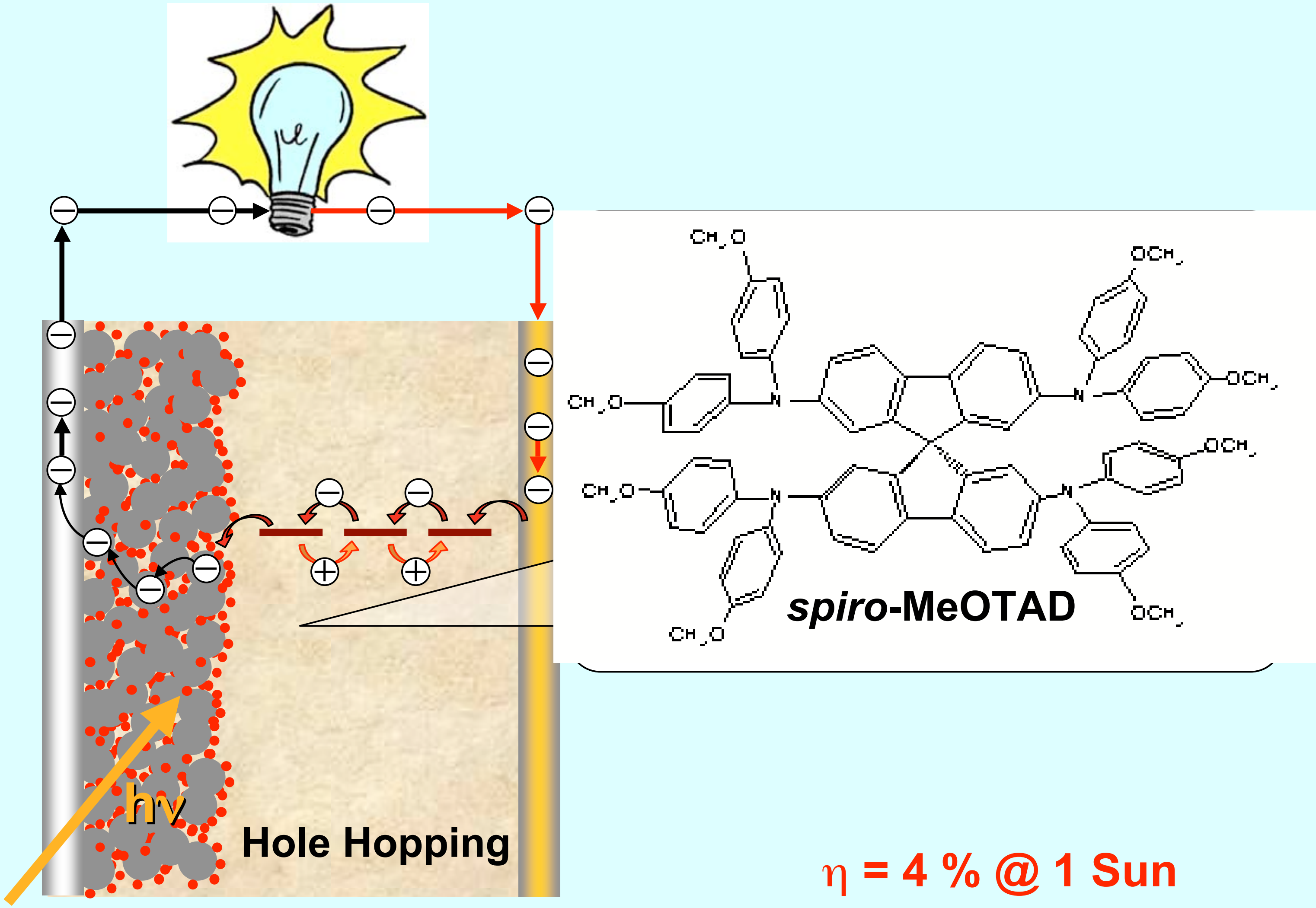




M. Grätzel, Nature 2001, 414, 338–344.

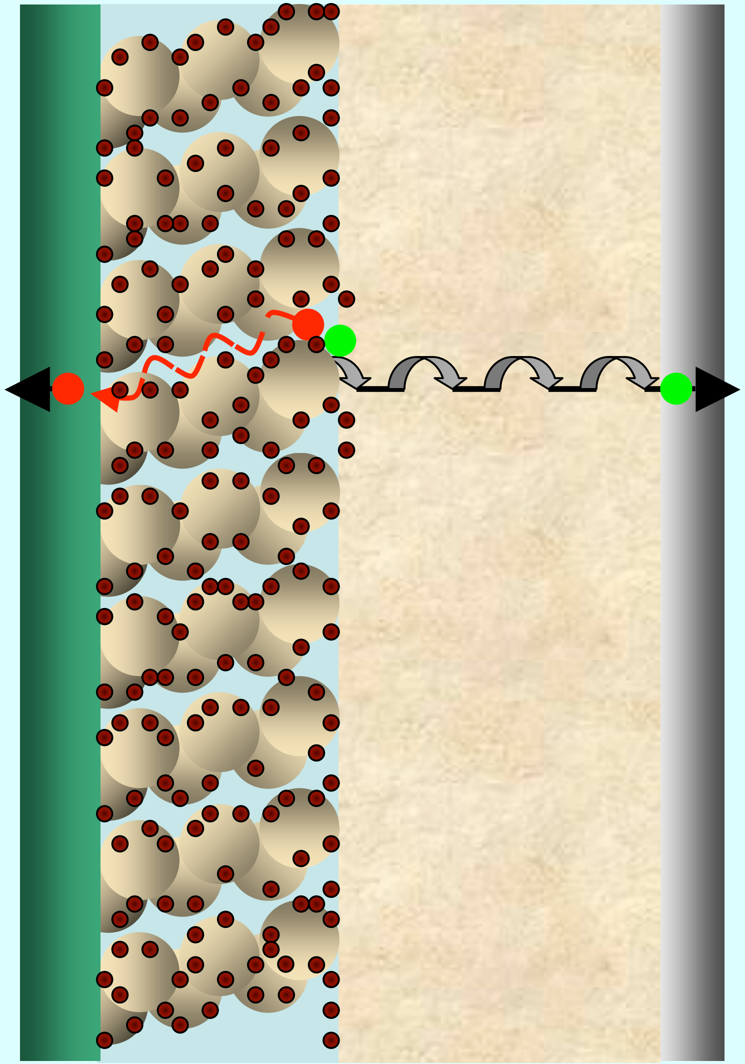
B. O'Regan, M. Grätzel, Nature 1991, 353, 737–740

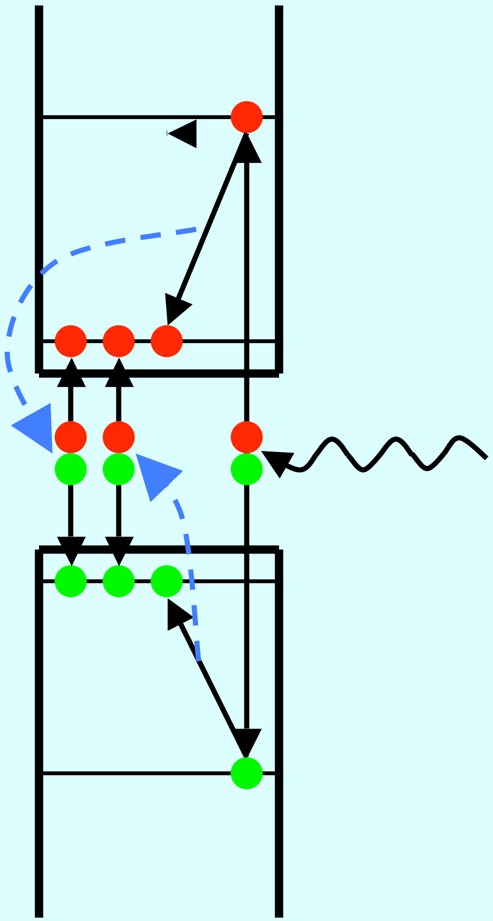
Device Concept: “solid-state”



η = 4 % @ 1 Sun

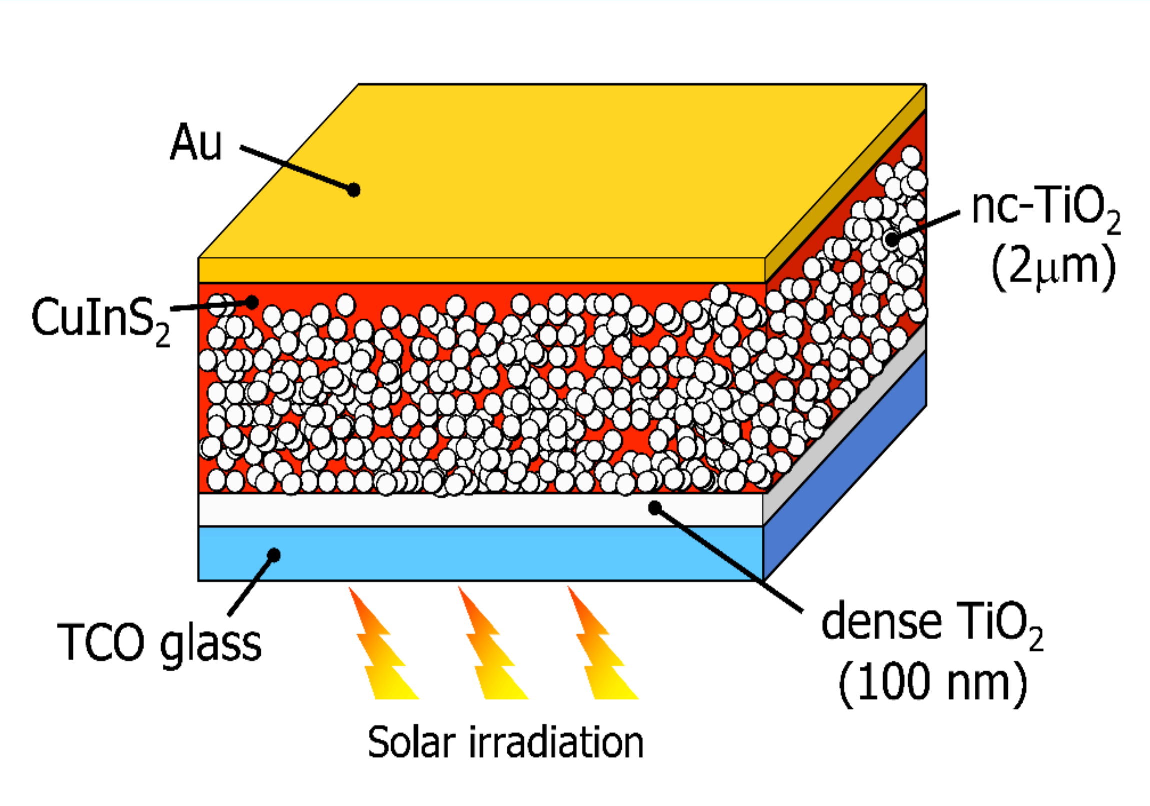
U. Bach, D. Lupo, P. Comte, J.-E. Moser, F. Weissörtel, J. Salbeck, H.Spreitzer and M. Grätzel, NATURE 395, 583-585 (1998)





R.D. Schaller and V.I. Klimov, Phys. Rev. Letts, 92, 186601 (May), 2004 (PbSe QDs)

3D solar cells

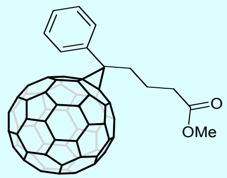


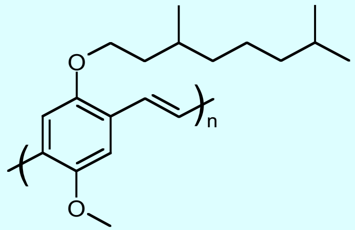
1 percolation of electrons and holes
2 selective contacts
3 no electrical shunts (pinholes)
4 stoichiometric TiO_2
5 p-type $CuInS_2$
6 buffer layer
7 intimate contact
8 complete filling of pores

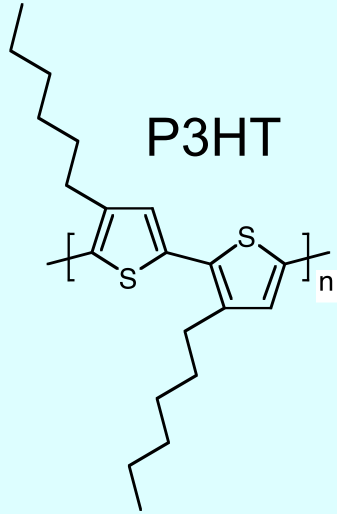
M. Nanu, J. Schoonman, and A. Goossens, Advanced Materials 16 (2004) 453
M. Nanu, J. Schoonman, and A. Goossens, Adv. Func. Mat. 15 (2005) 95

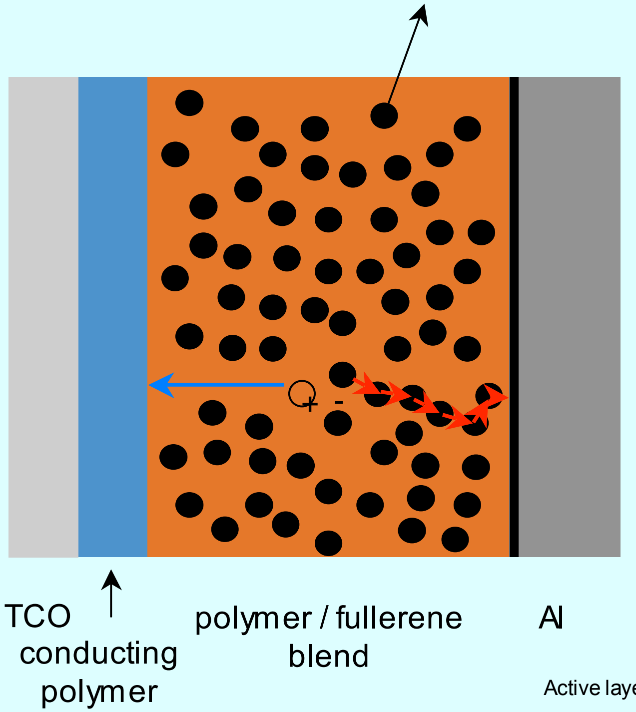
Bulk organic heterojunction solar cell

PCBM blended with: OC_1C_{10}-PPV P3HT





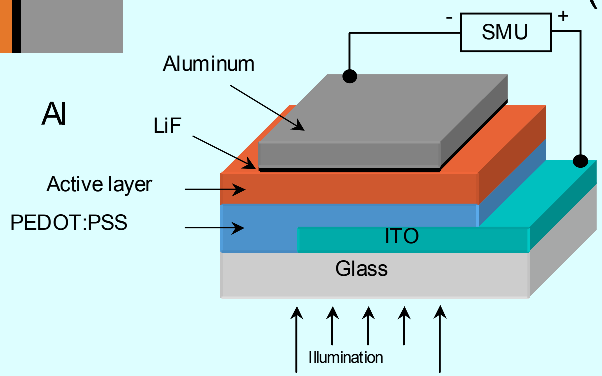


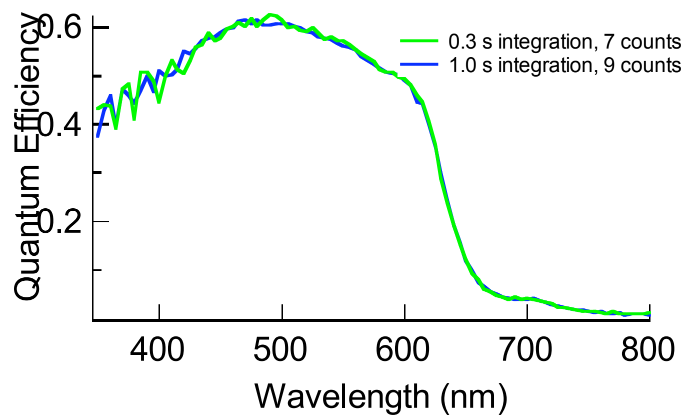


J_{SC} = 5.3 mA/cm²
V_{OC} = 0.82 V
FF = 61%
η = 2.5%

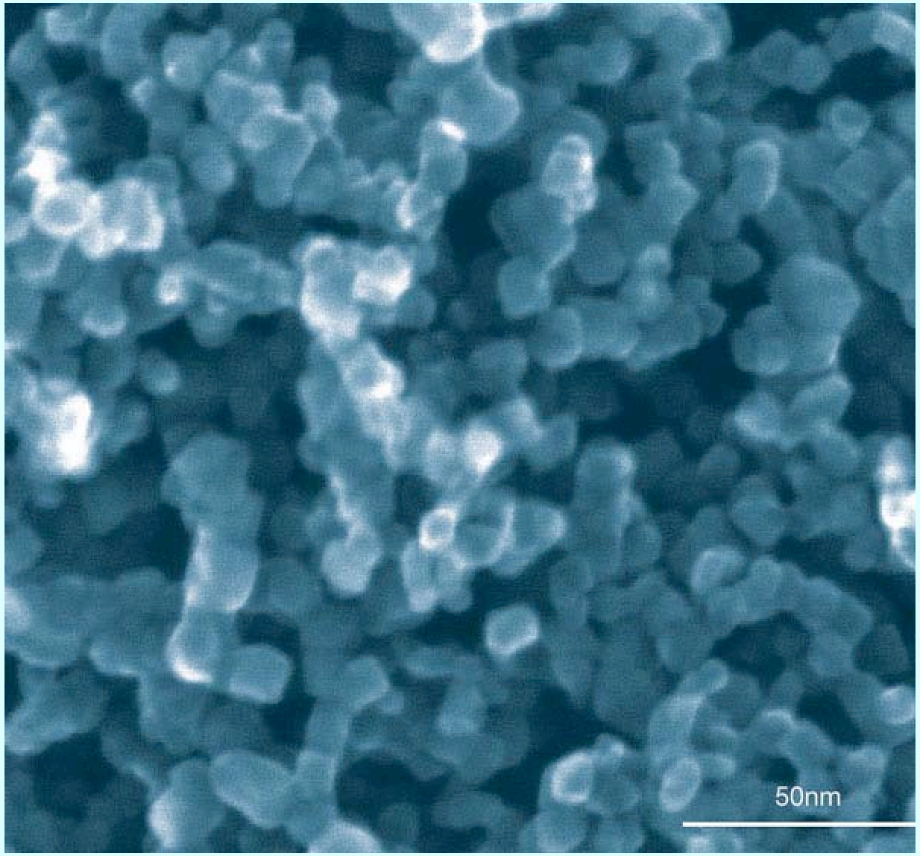
J_{SC} = 9.3 mA/cm²
V_{OC} = 0.56 V
FF = 60%
η = 3.5%

(under AM1.5 illumination)





From G. Rumbles NREL



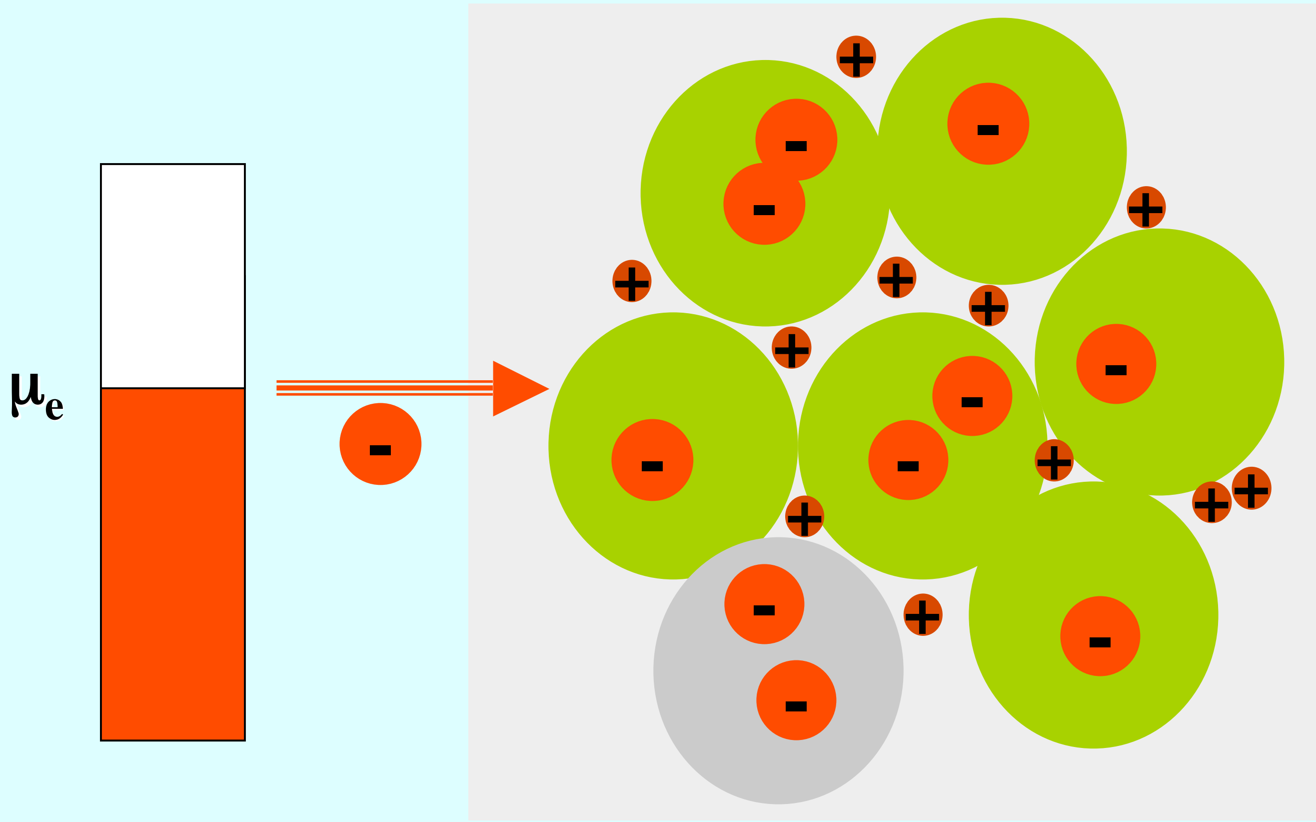
Outline

- Mesoporous junctions, interfacial and cross-surface charge transfer
- Photoinduced charge separation
- Photogalvanic generation of electricity from sunlight

Mesoscopic semiconductor films exhibit extraordinary properties

- surface amplification ca 100 times for each micron film thickness
- Interpenetrating network electronic junction having huge contact area
- ease of electron percolation through the particle network
- very rapid lithium insertion and release
- high photocatalytic activity
- high sensitivity for detecting ambients
- efficient photovoltaic energy conversion

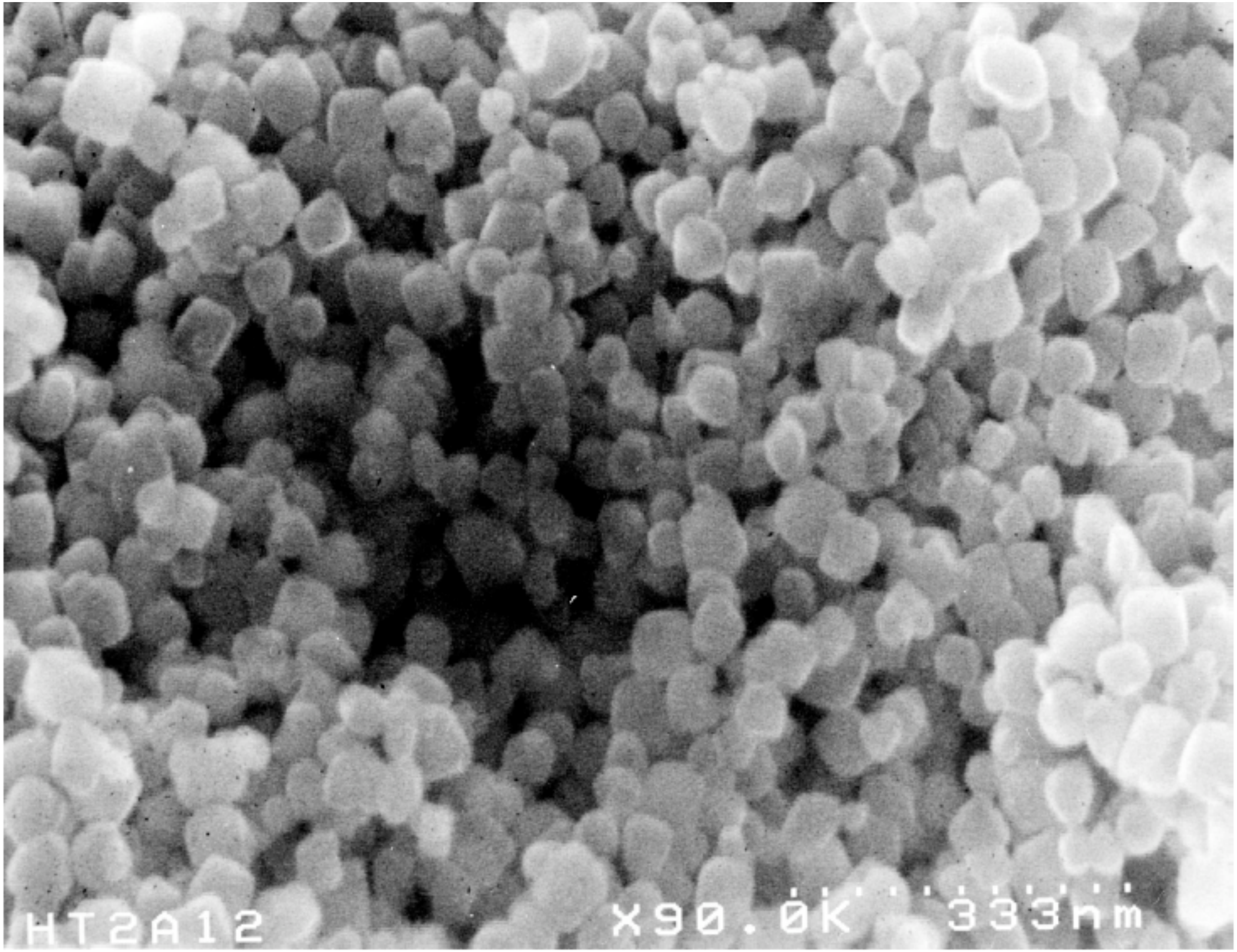
Rapid electron percolation through nanocrystals



Charge of electrons compensated by inert positive ions in electrolyte

No space charge limitation of current !

G. Rothenberger, M Grätzel and D Fitzmaurice, *J.Phys Chem*.**1992**,96,5983



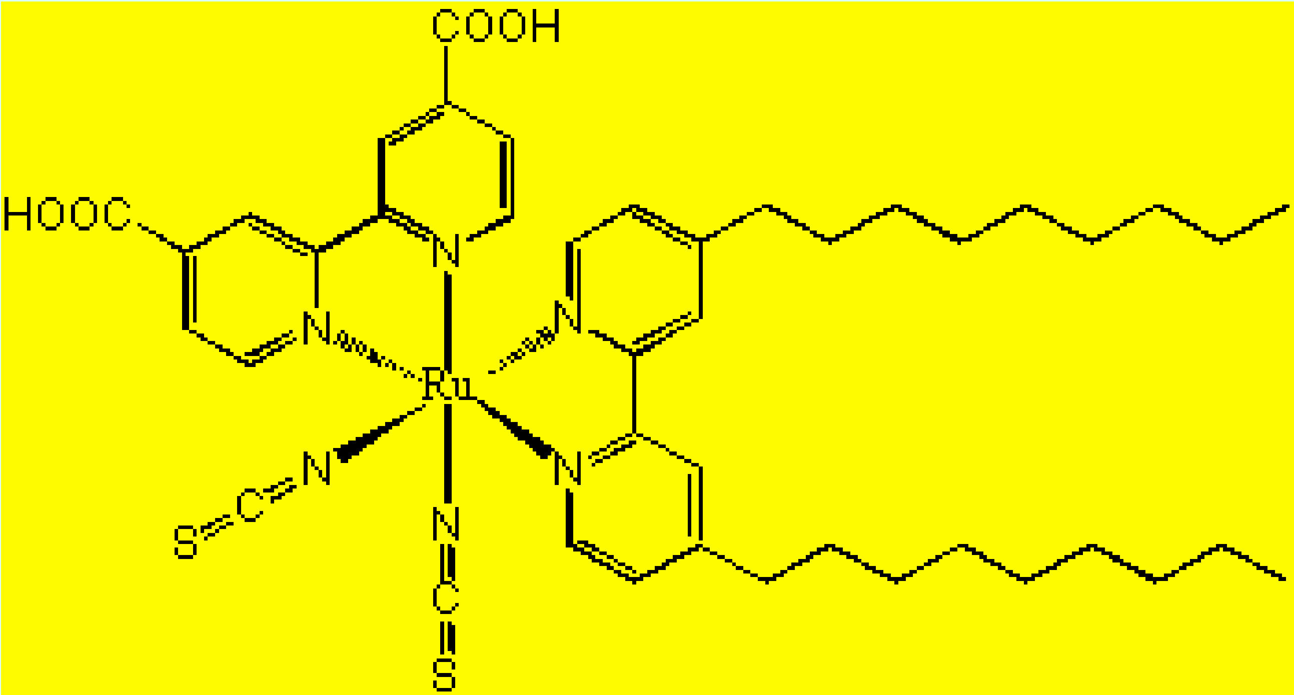
Kavan M. Grätzel *Electrochemical and Solid State Letters* 5 (2): A39-42 (2002)

Molecular wiring of insulating Nanocrystals

Cross surface electron and hole transfer in self-assembled molecular charge transport layers

Ambipolar lateral charge percolation in self-assembled monolayers on nanocrystalline insulator films

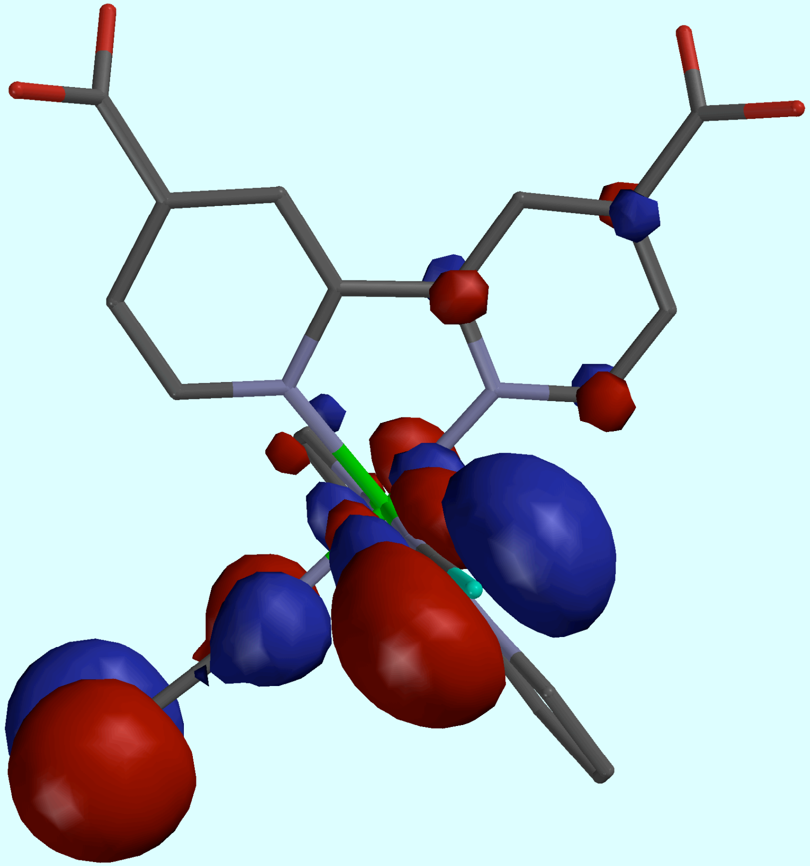
Z907 sensitizer

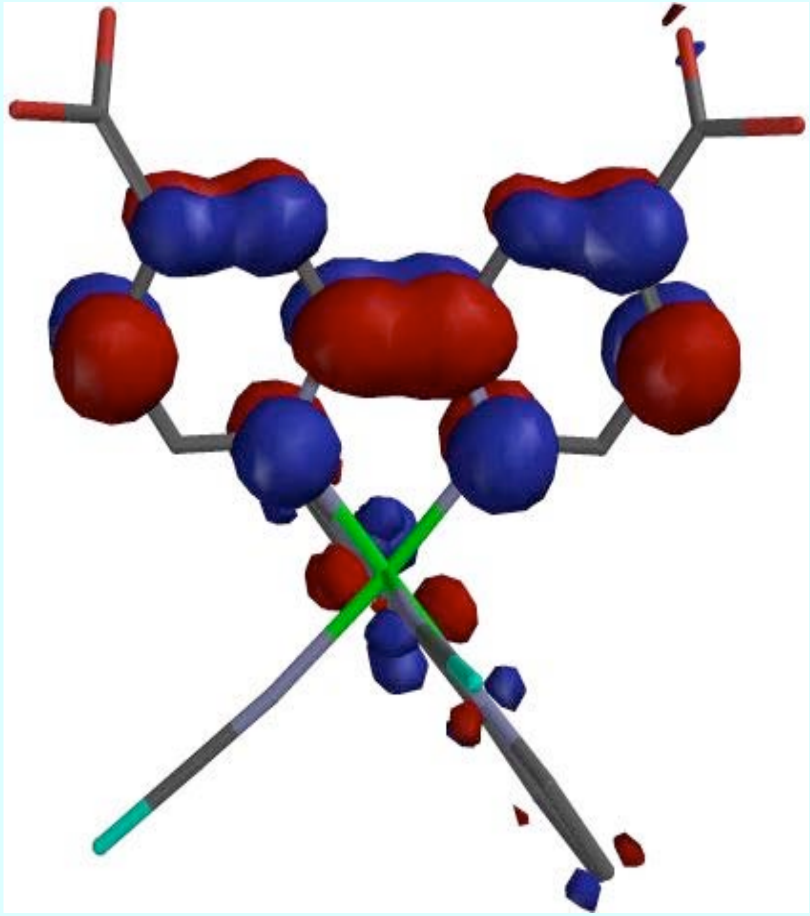


P.Wang, S.M. Zakeeruddin, R. Humphry-Baker, J.-E. Moser, M. Grätzel
Adv. Materials, **15, No. 24, 2101-2104 (2003)**

HOMO

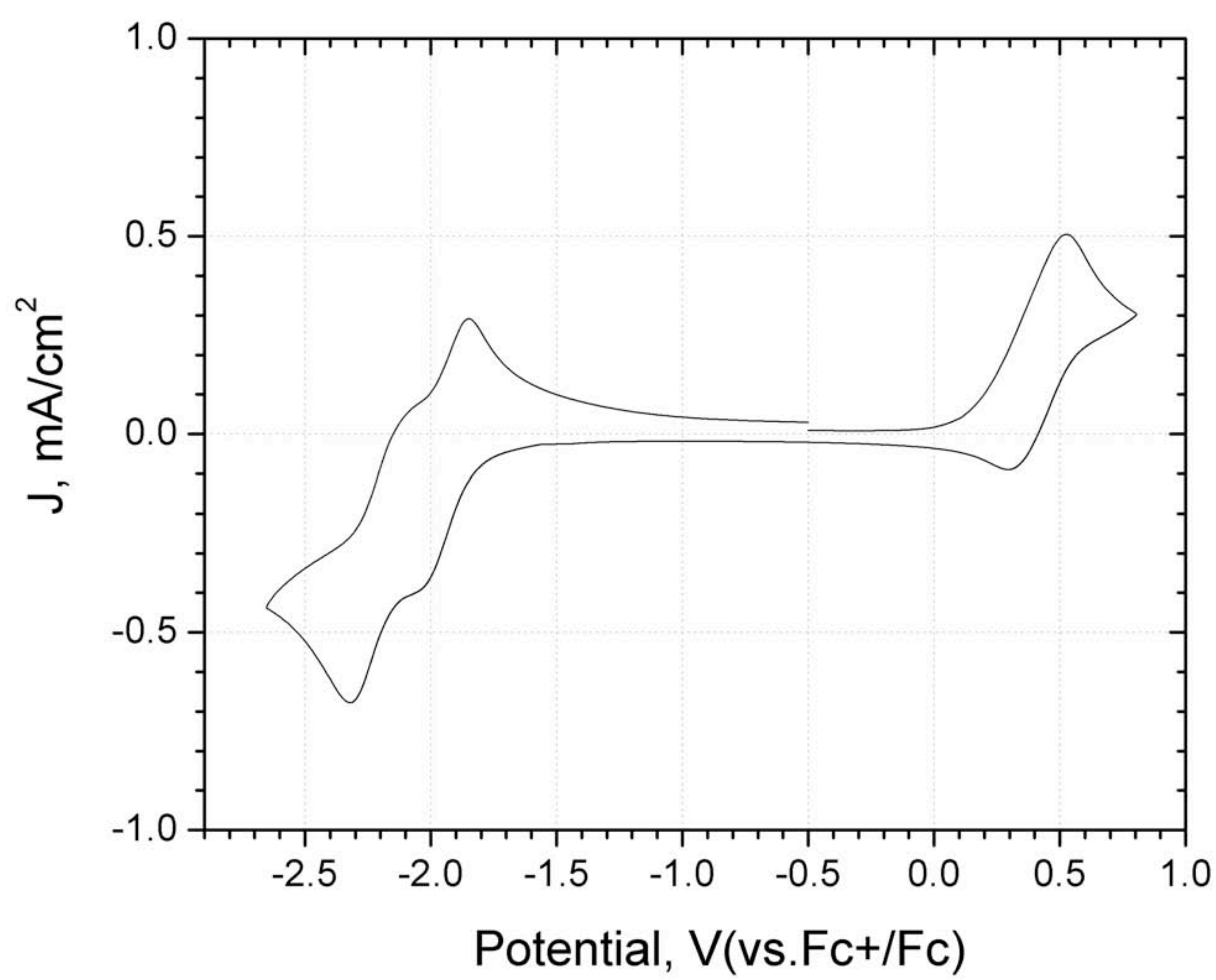
LUMO





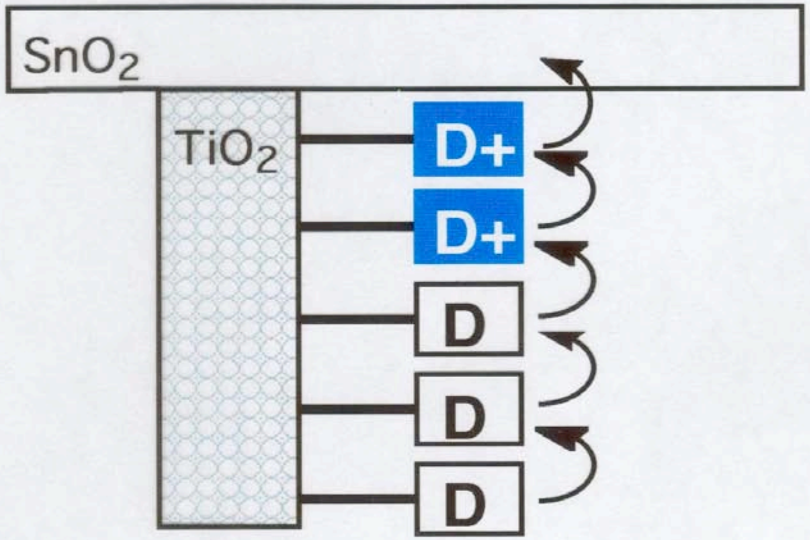
A. Hagfeldt, M. Grätzel, Acc. Chem. Res. 2000, 33, 2679–27

Cyclic Voltammogram of Z 907 on Aluminium Oxide Film



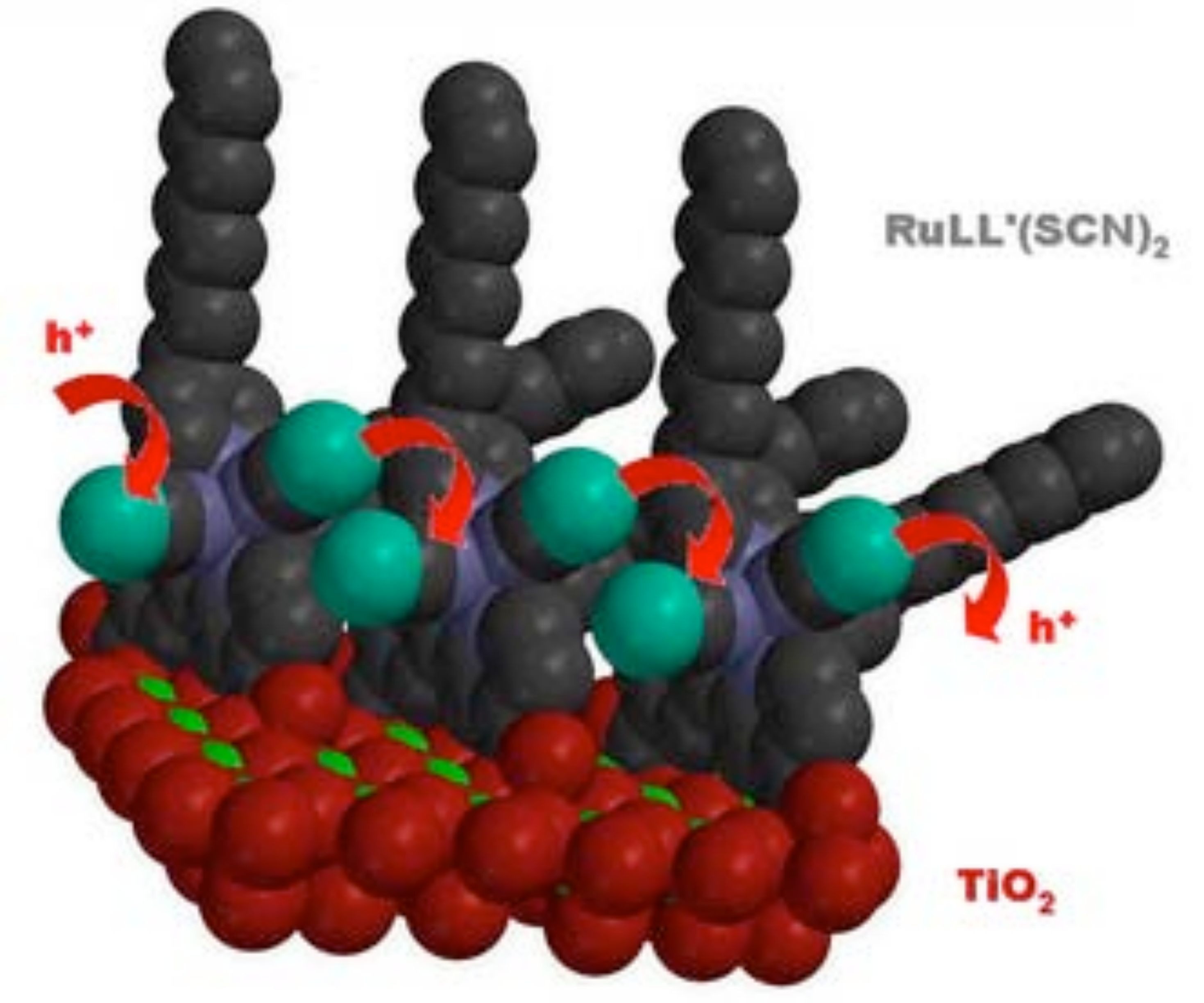
Electrolyte; EMITFSI in Acetonitrile, Scan rate= 0.1V Sec^{-1}

2. Hole injection from the conductive support followed by lateral charge transport inside the monolayer



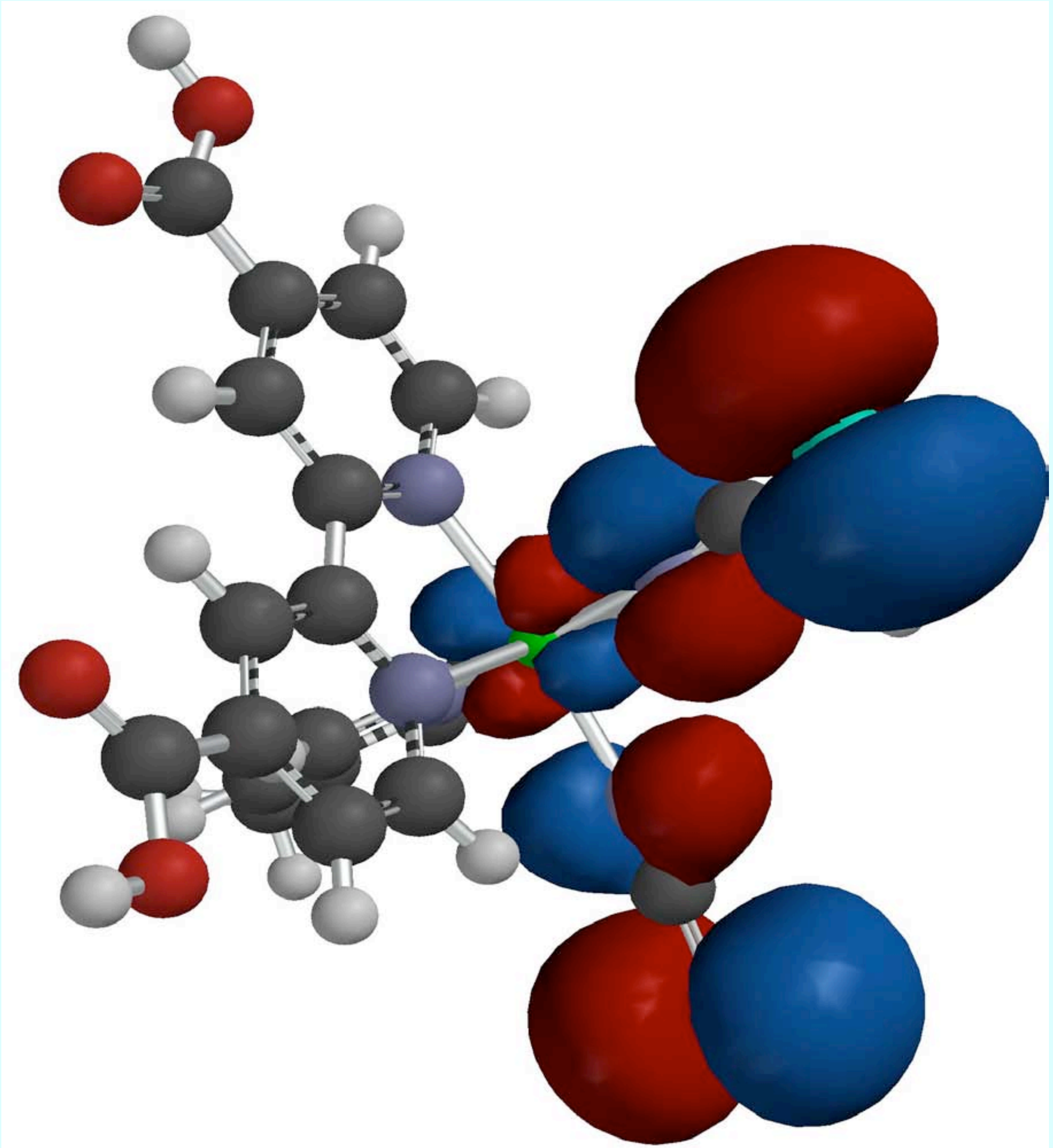
Properties:

- D_{app} dependent of the surface concentration
- Percolation thershold

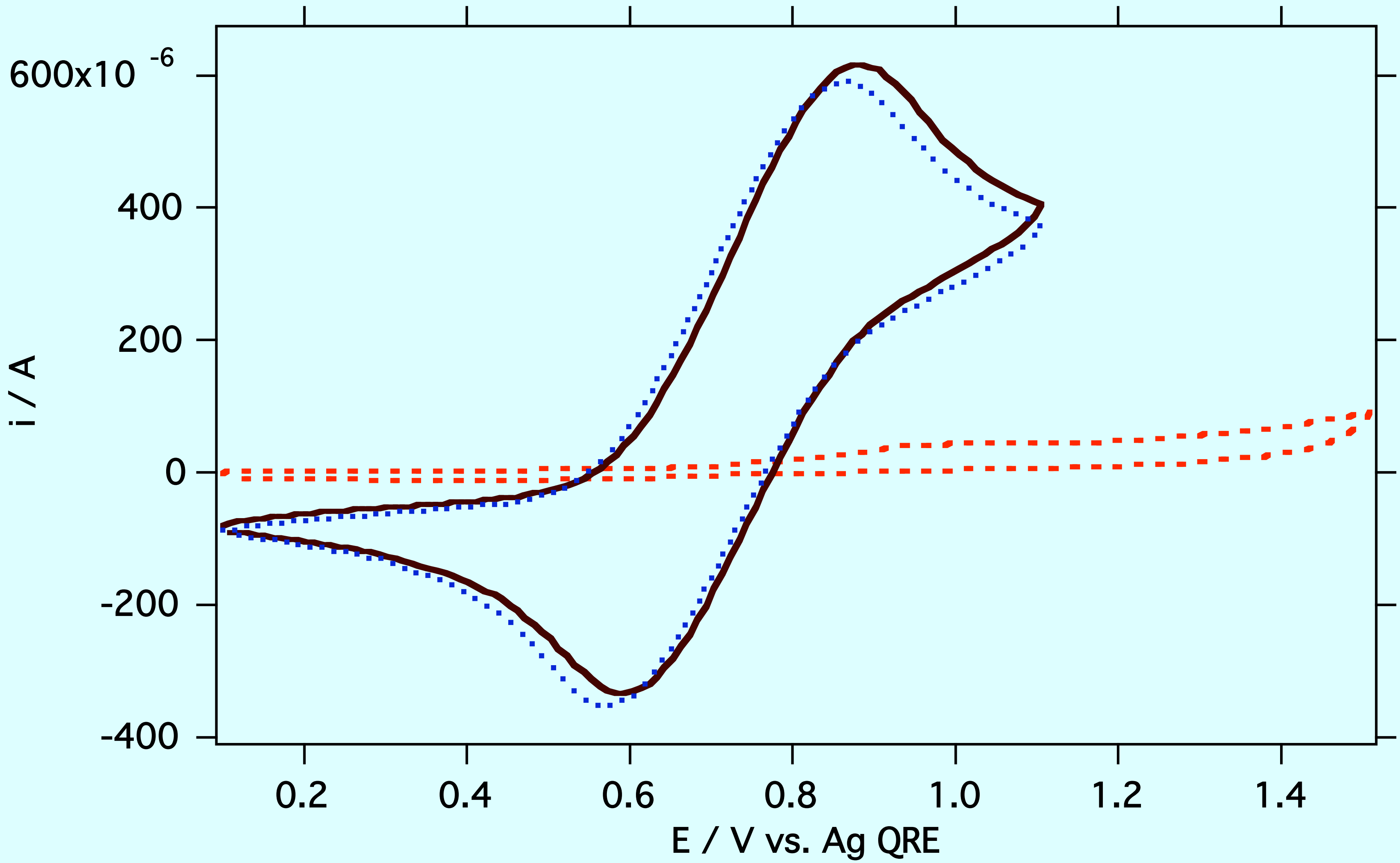


Cross surface hole percolation through a self-assembled Z-907 monolayer adsorbed on mesoscopic anatase TiO_2.

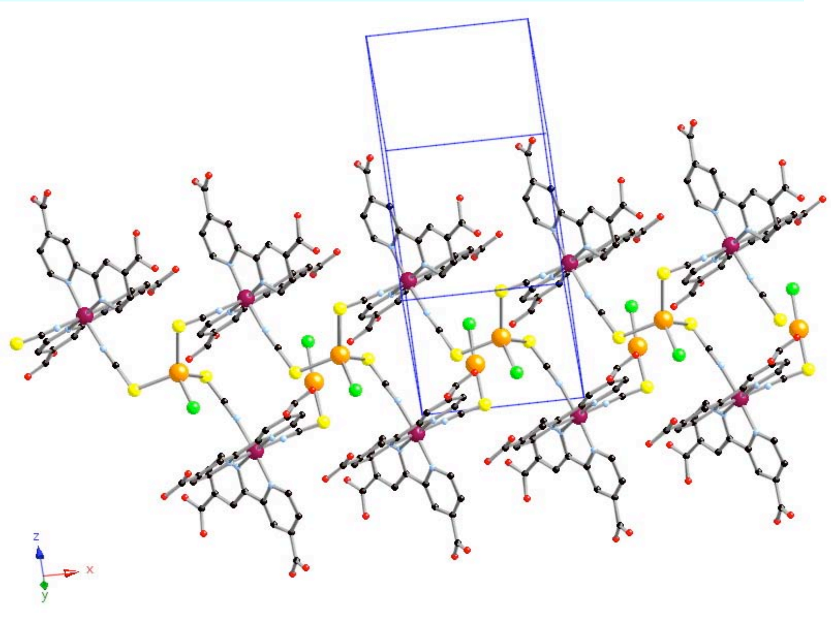
QING WANG, ROBIN HUMPHRY BAKER AND MICHAEL GRAETZEL to be submitted

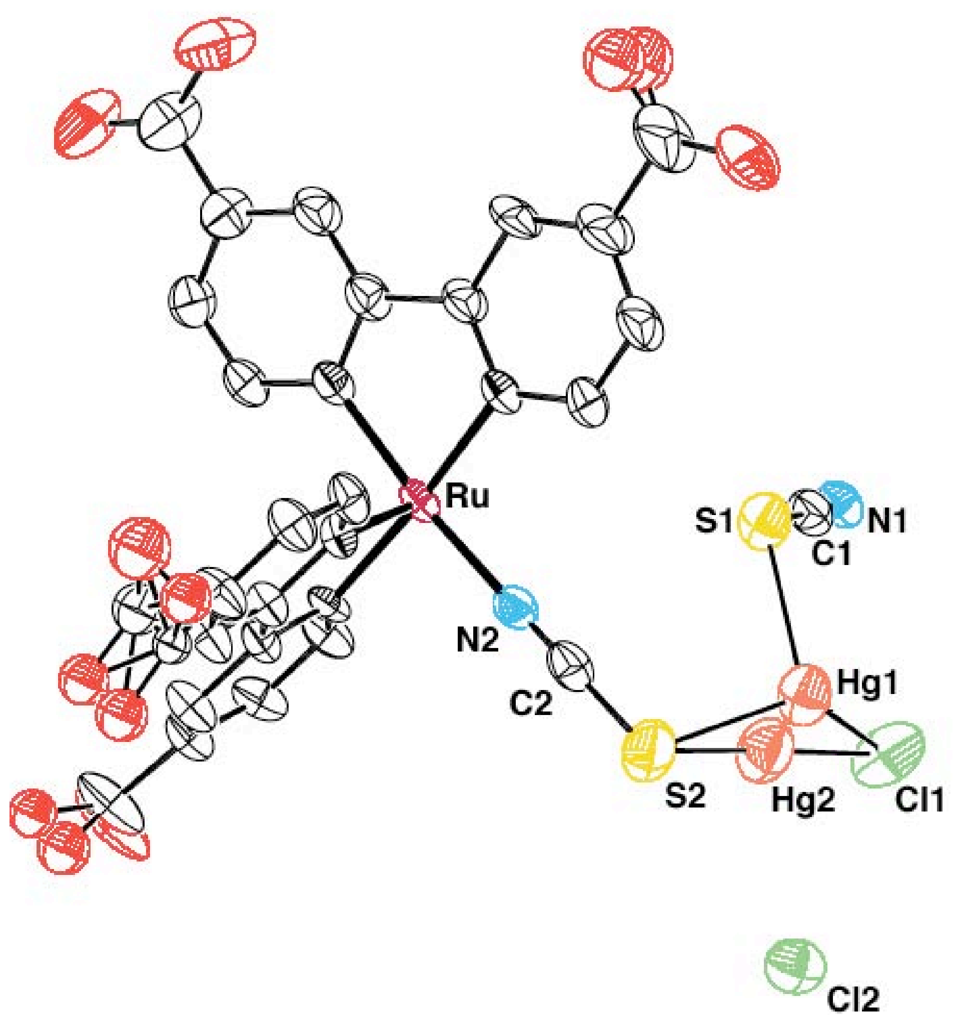


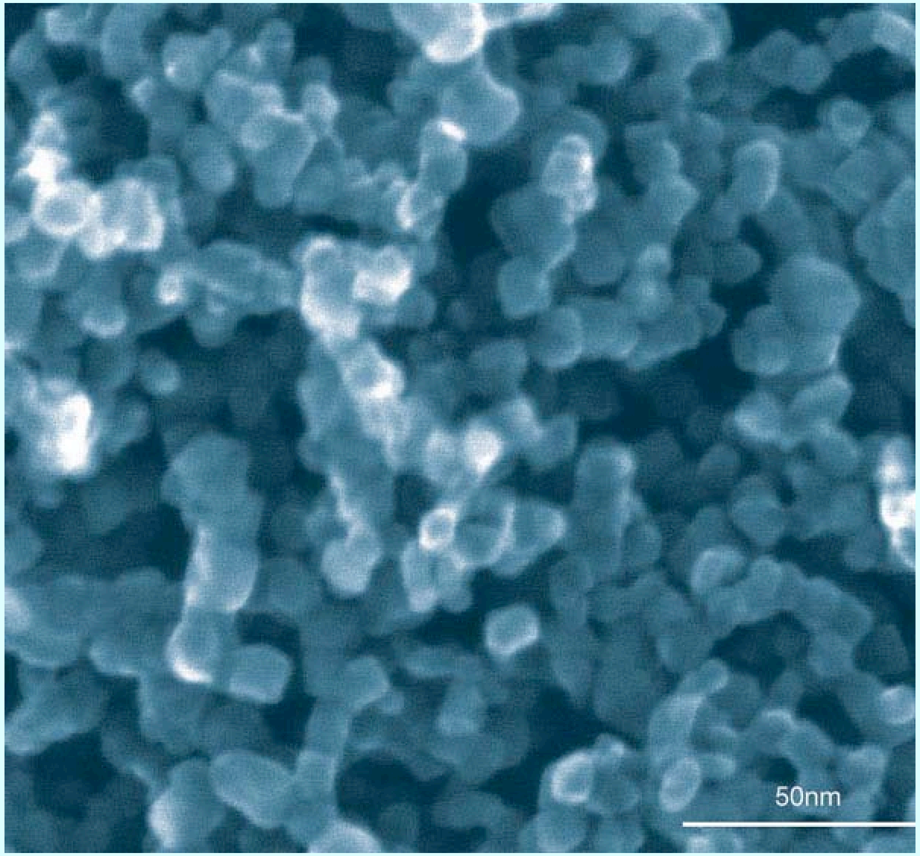
Cyclic voltammogram of the N621 complex anchored onto a TiO_2 electrode (black line), exposed to the solutions of $HgCl_2$ (red dashed dotted line) and $Pb(ClO_4)_2$ (blue dashed line)



Molecular structure of the **N719**-$HgCl_2$ complex showing the asymmetric unit which contains one mercury atom, and two Cl^- anions







Outline

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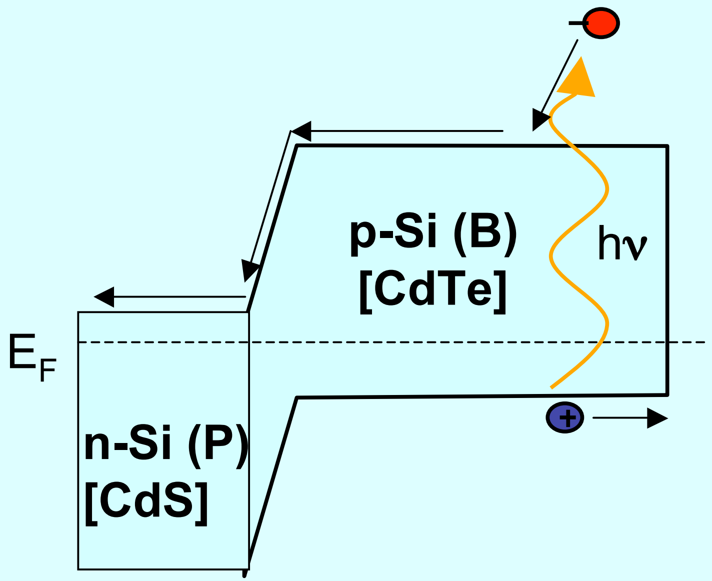
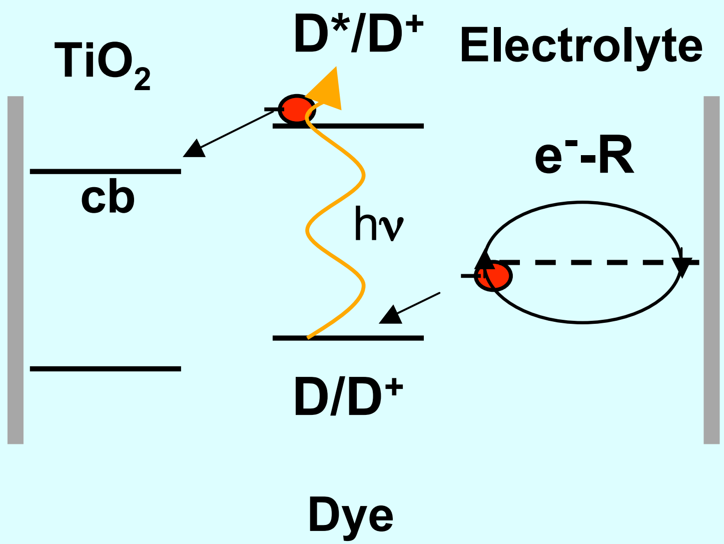
- Photoinduced charge separation
- Photogalvanic generation of electricity from sunlight

Silicon Photovoltaic Cells

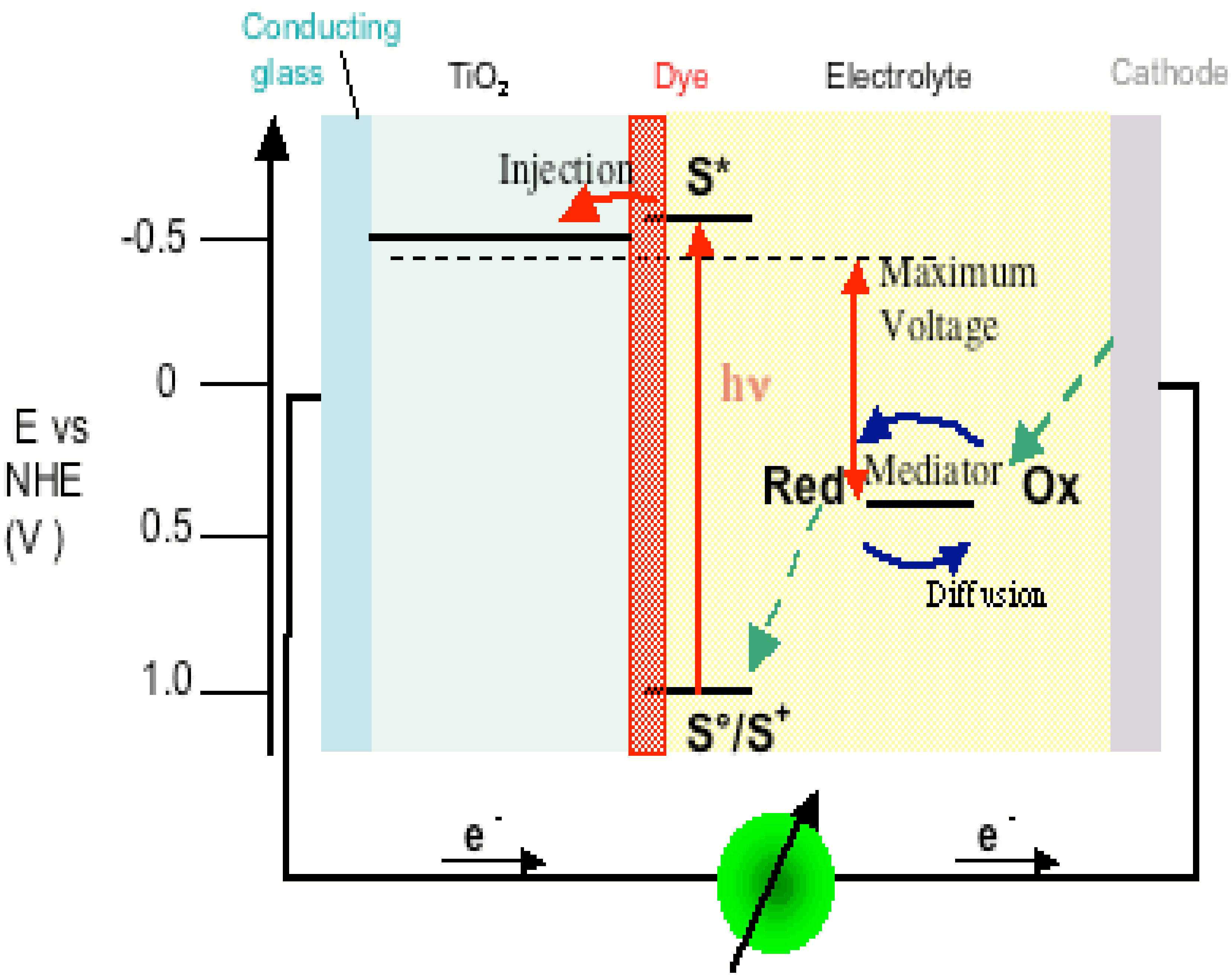


Charge separation by electric field within a p- and n-doped semiconductor material (Si, II-VI, a-Si: H)

Dye Solar Cells



Charge separation by kinetic competition like in photosynthesis



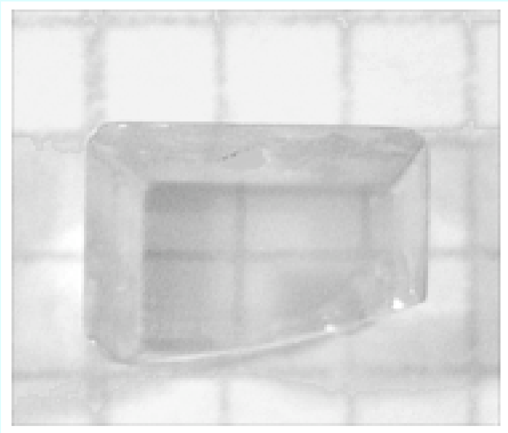
Conducting glass
TiO2
Dye
Electrolyte
Cathode
Injection
S*
-0.5
Maximum Voltage
0
hν
E vs NHE (V)
Red
Mediator
Ox
0.5
Diffusion
1.0
S°/S+
e-
e-

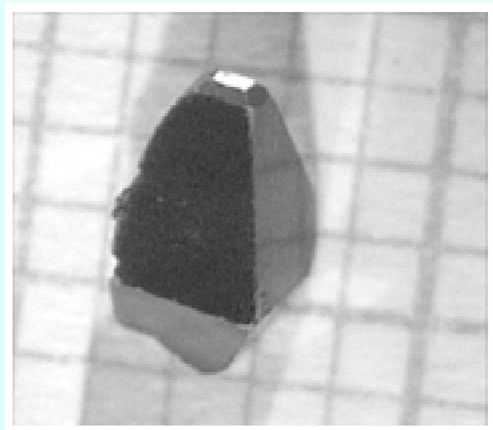
The two dilemmas of light harvesting by surface immobilized molecular absorbers

1. A monolayer of dye on a flat surface absorbs at most a few percent of light because it occupies an area that is much larger than its optical cross section

2. Compact semiconductor films need to be n-doped to conduct electrons. Energy transfer quenching of the excited sensitizer by the electrons in the semiconductor leads to conversion of light to heat reducing photovoltaic conversion efficiency.

Anatase crystals

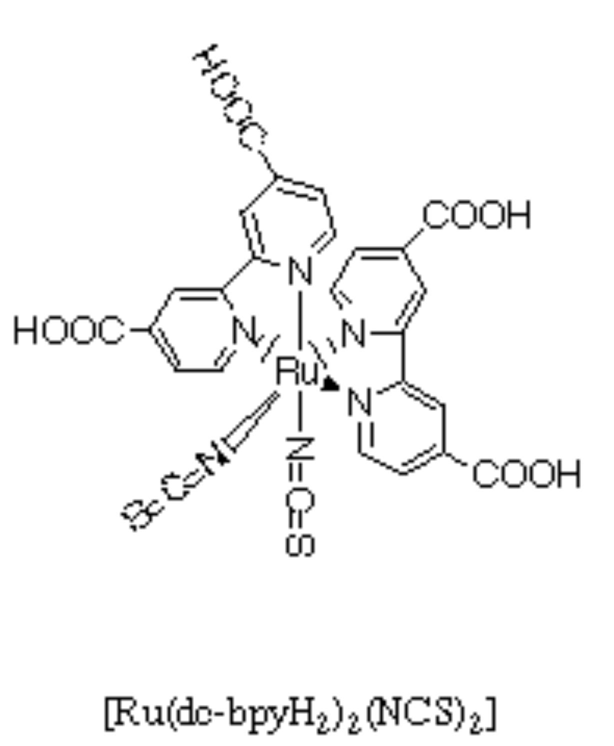


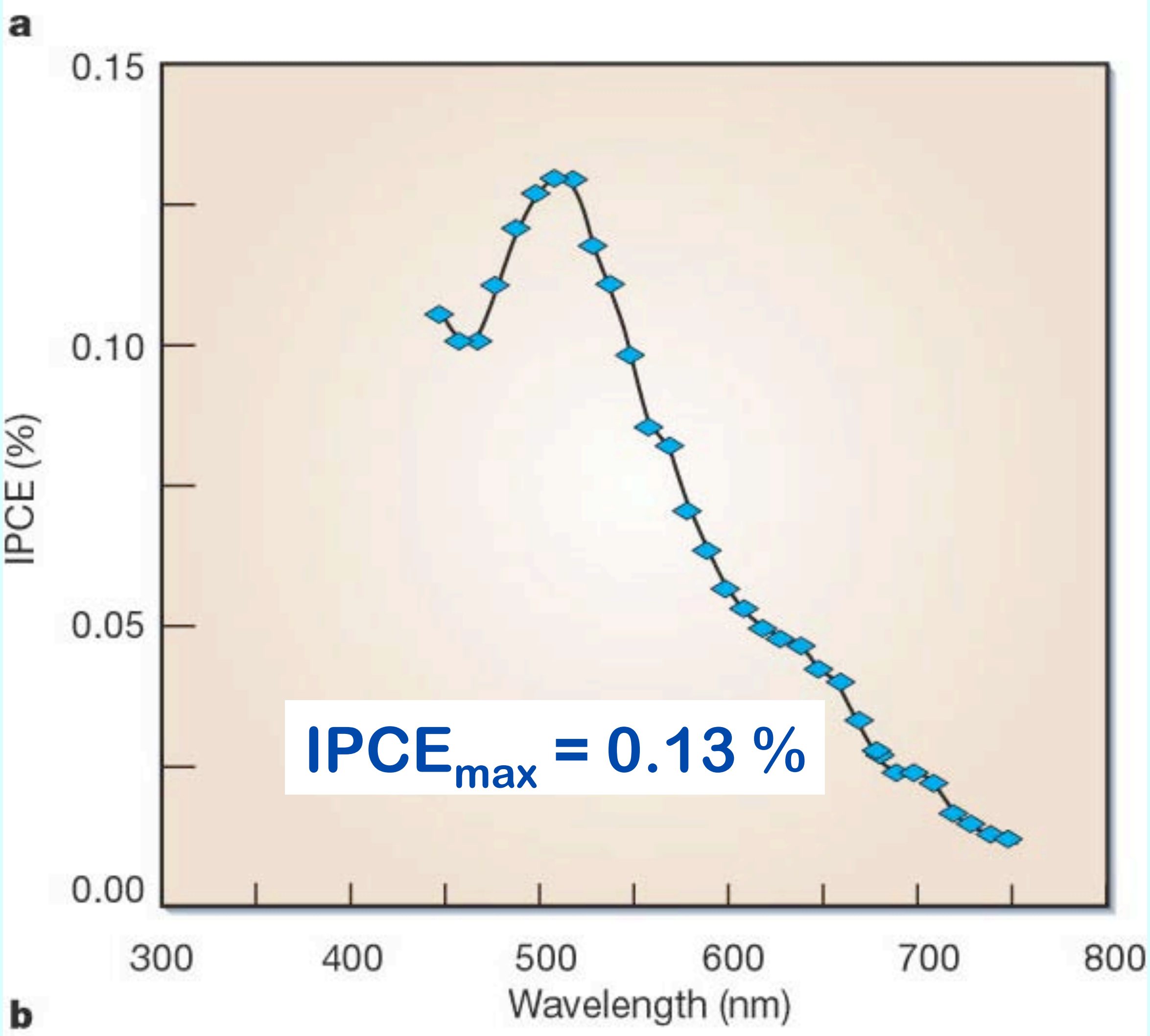


- Undoped crystal, (001) surface
- Doped crystal, (101) surface

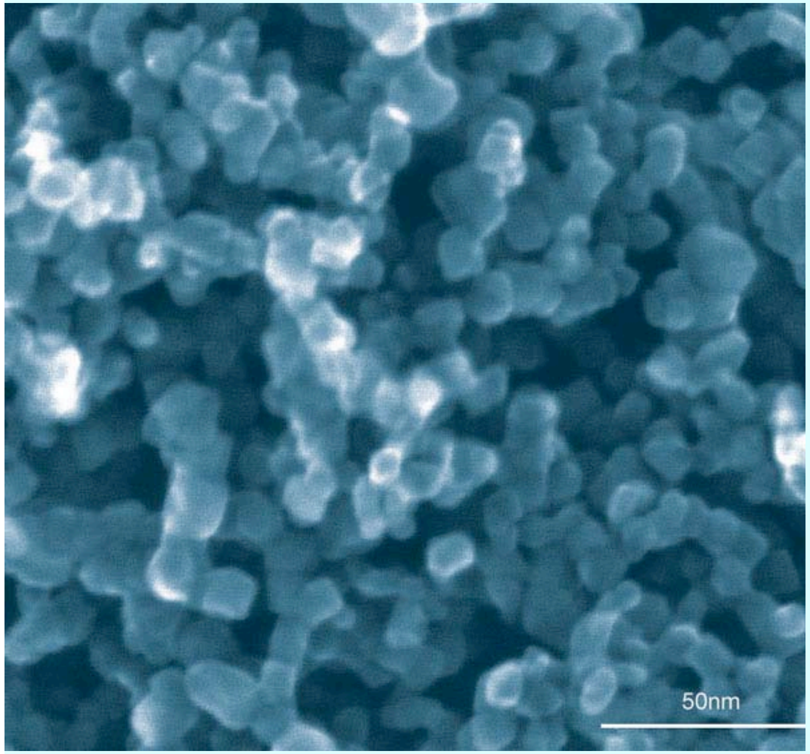
A. Vittadini, A. Selloni, F. Rotzinger and M. Grätzel Phys. Rev. Lett. 81, 2954 (1998)

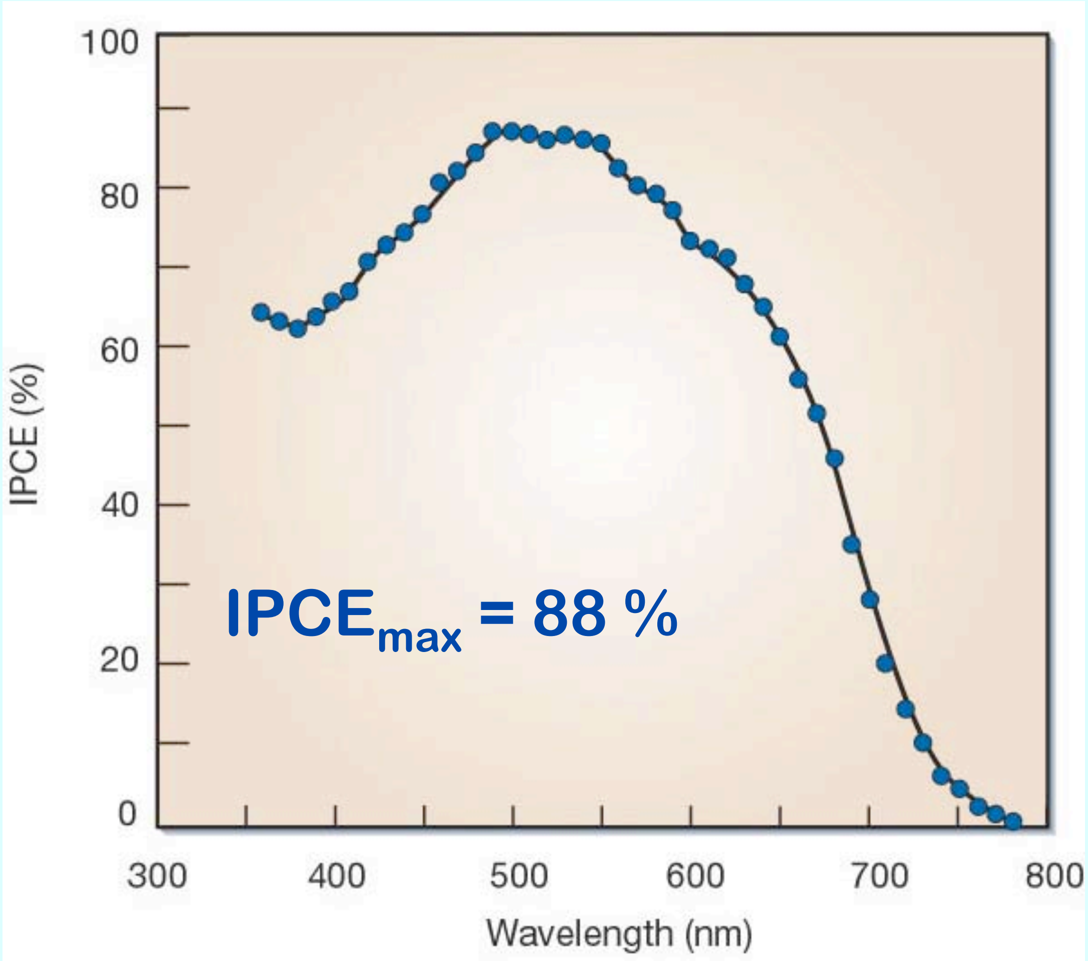
Incident photon to electron conversion efficiency (IPCE) of a dye-sensitized TiO_2 (101) single crystal PEC solar cell

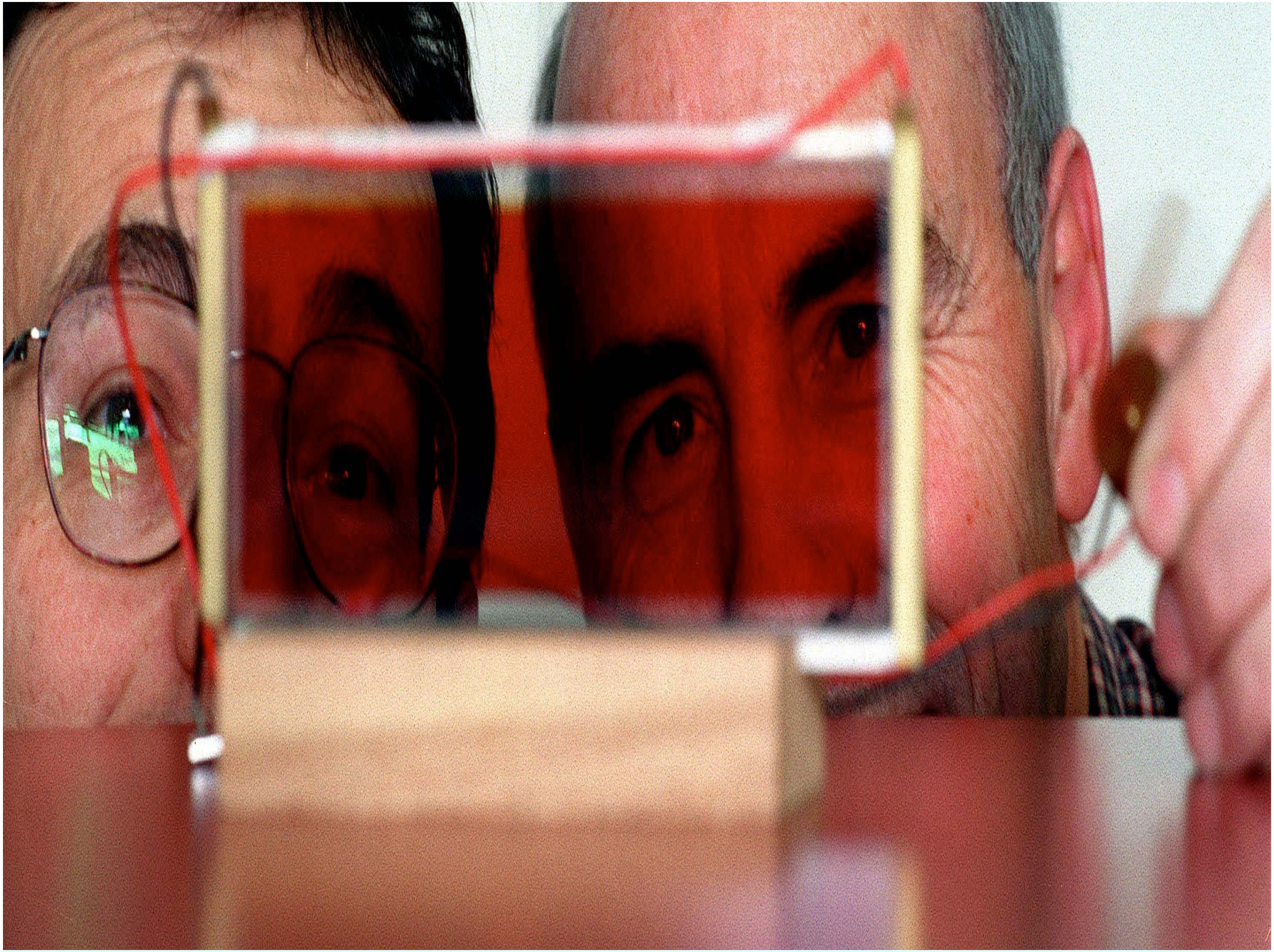


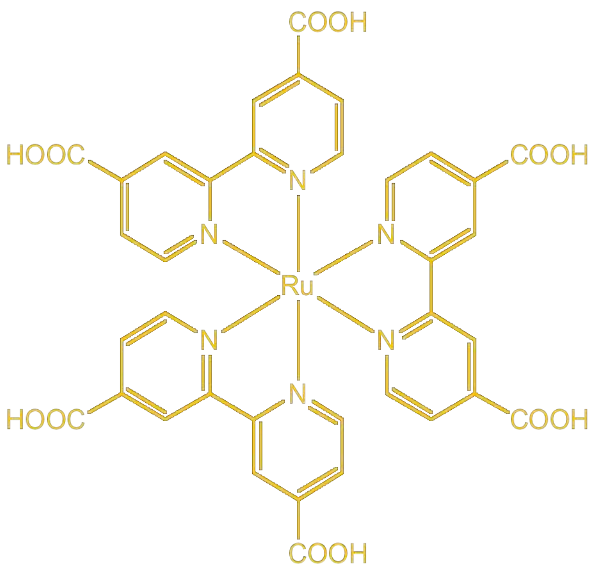


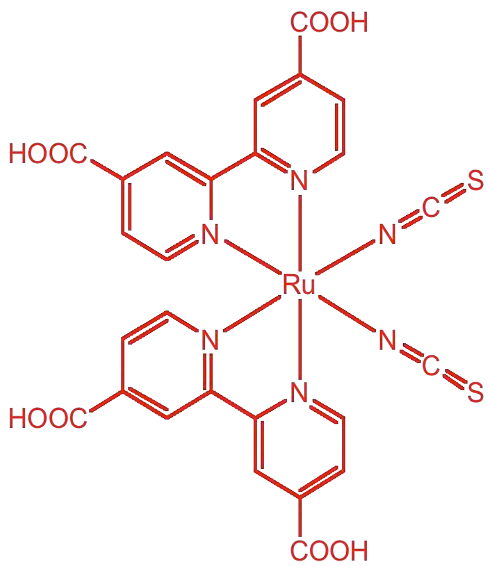
Incident photon to current conversion efficiency of a dye-sensitized solar cell based on a mesoscopic TiO_2 electrode








COOH
HOOC
COOH
N
N
N
Ru
N
N
N
HOOC
COOH
COOH


COOH
HOOC
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C
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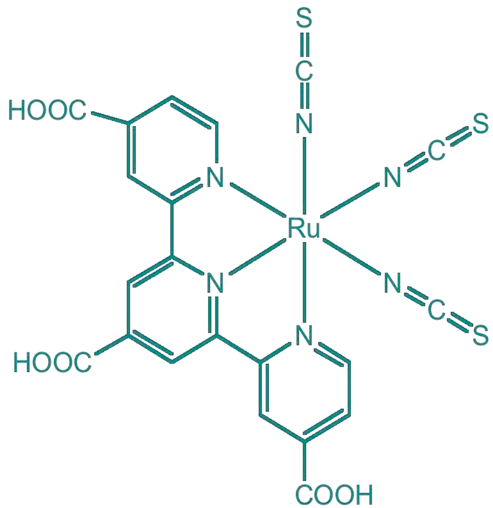
Ru
N
C
S
N
N
HOOC
COOH


S
C
N
HOOC
N
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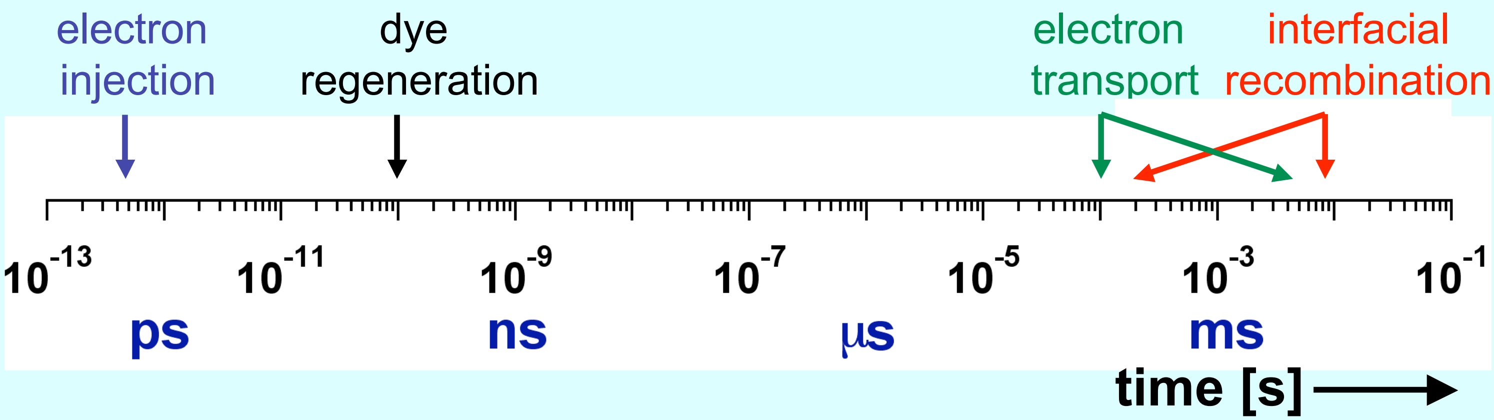
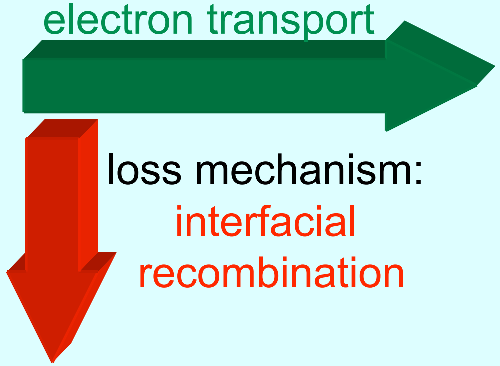
S
Ru
N
N
C
S
HOOC
N
COOH

Dye sensitized nanocrystals show quantitative conversion of the photons into electric current

Dynamic Competition





Competition ⇒

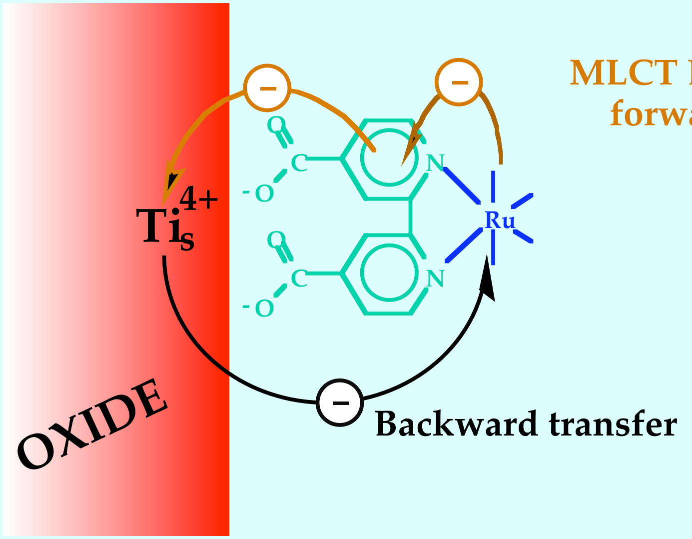
Electron diffusion length

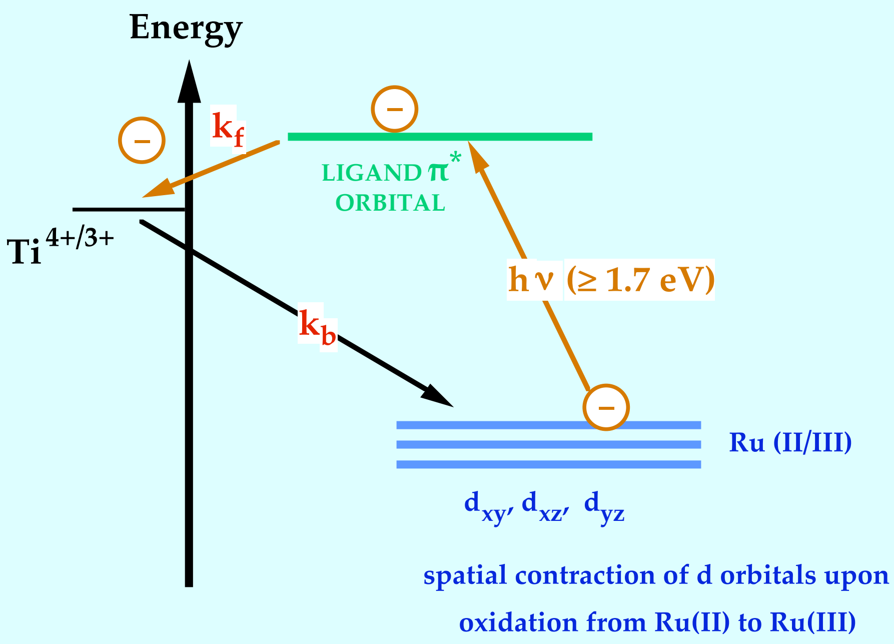
$$L_n = \sqrt{D_n \cdot \tau_n}$$

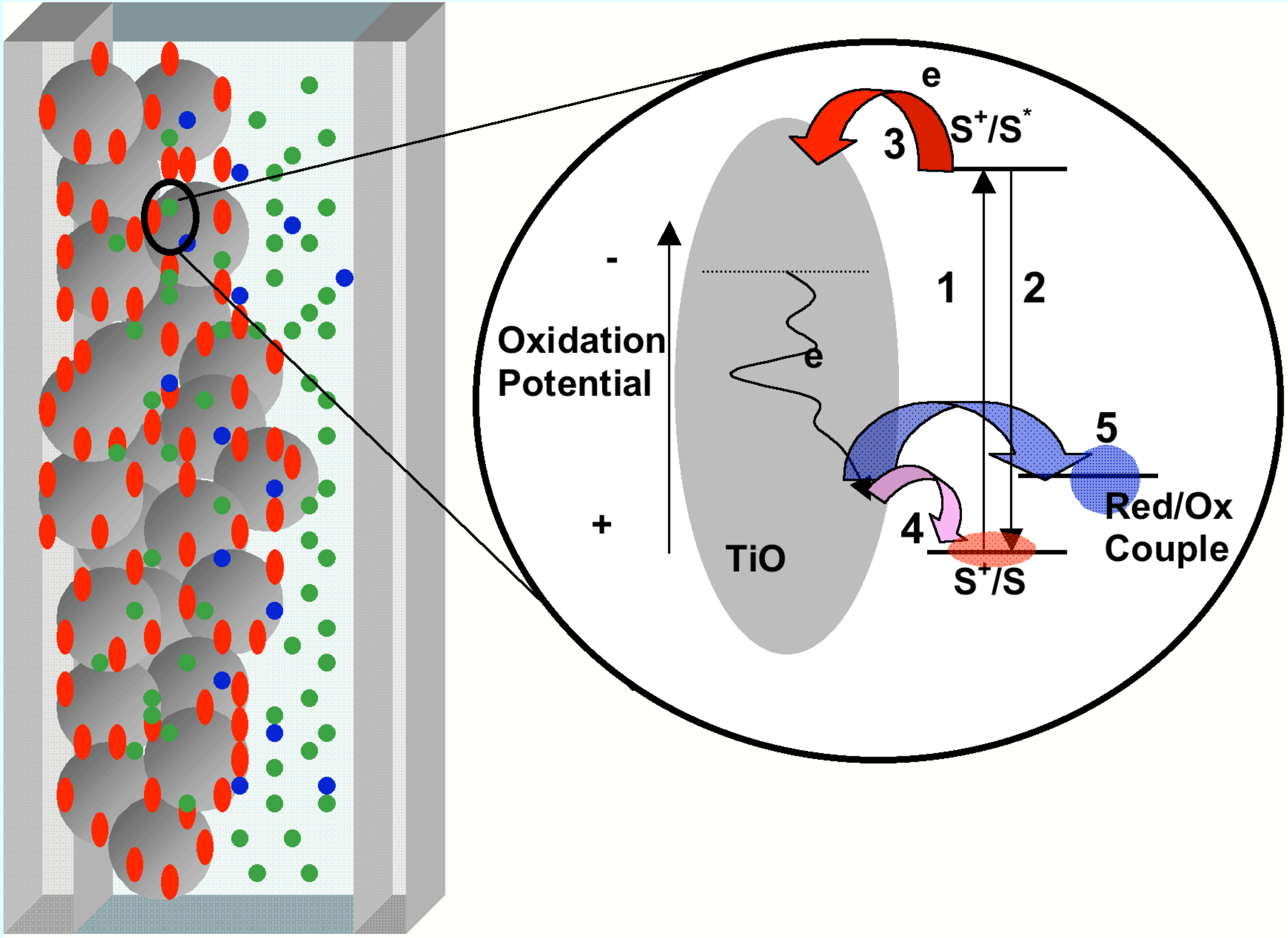
τ_n: electron lifetime

D_n: electron diffusion coefficient

Photo Induced Heterogeneous Electron Transfer Cycle

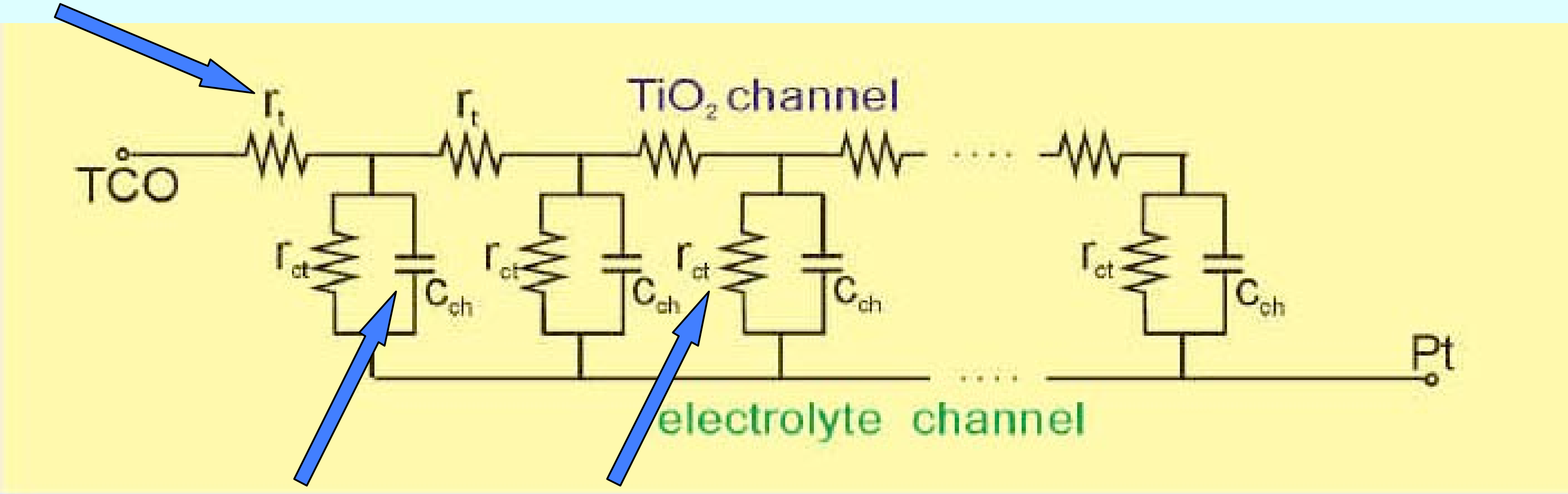




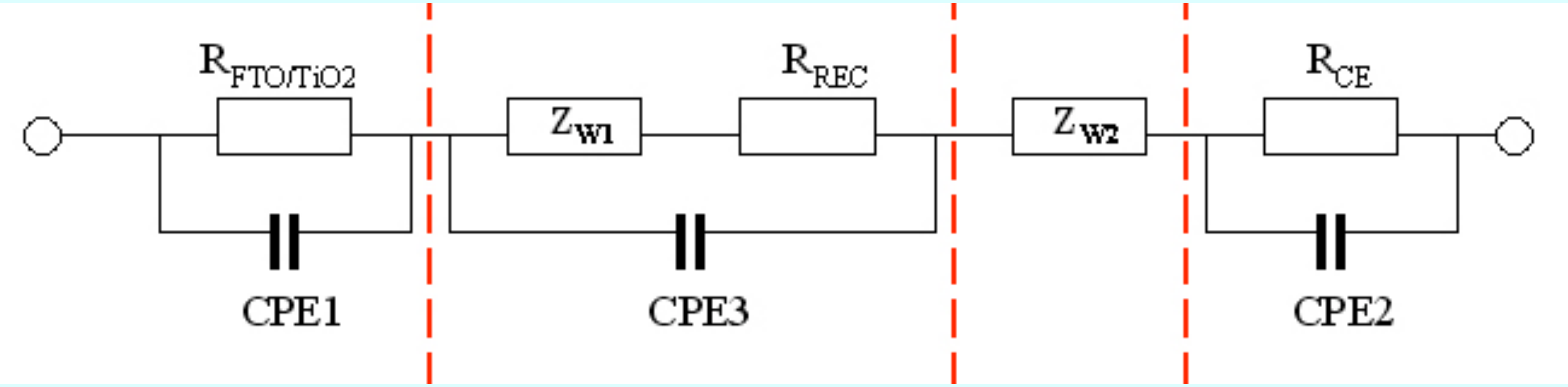

e
S^+/S^*
3
-
1
2
Oxidation
Potential
e
5
Red/Ox
Couple
+
4
TiO
S^+/S

Finite length transmission model (Bisquert)

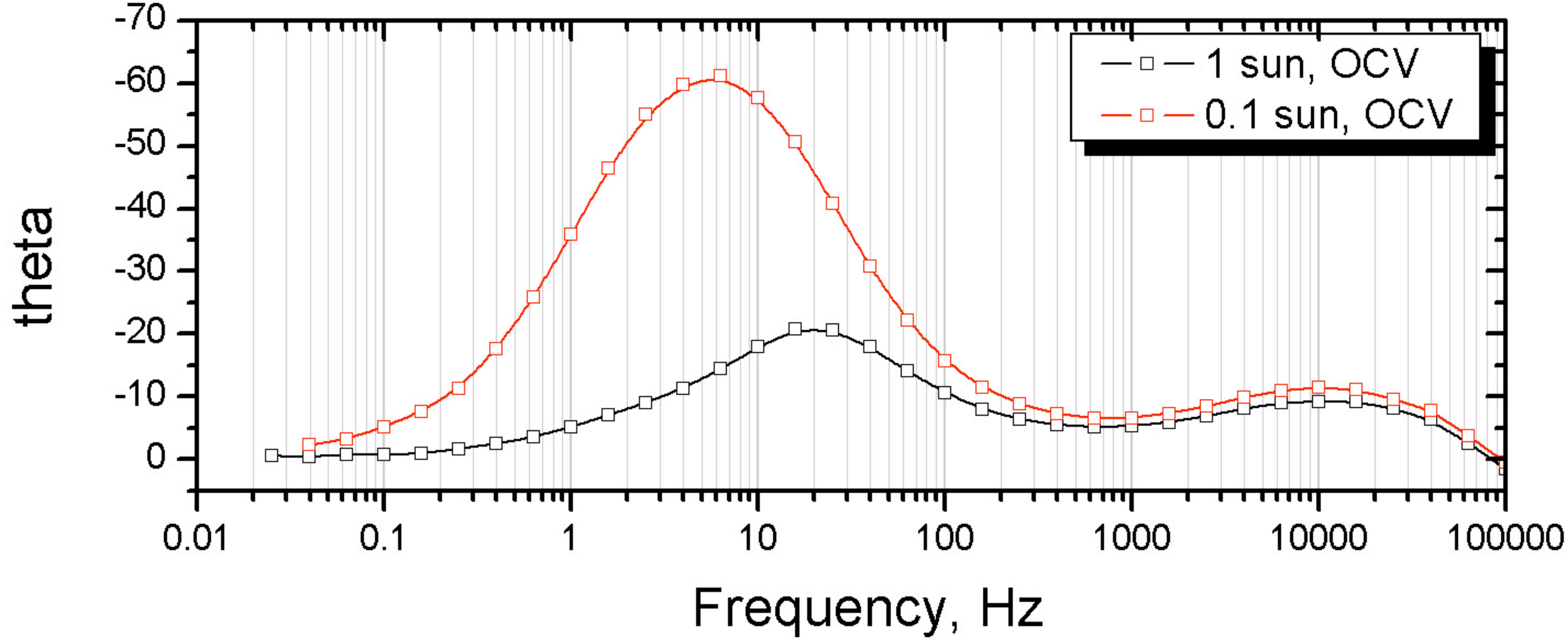
Transport



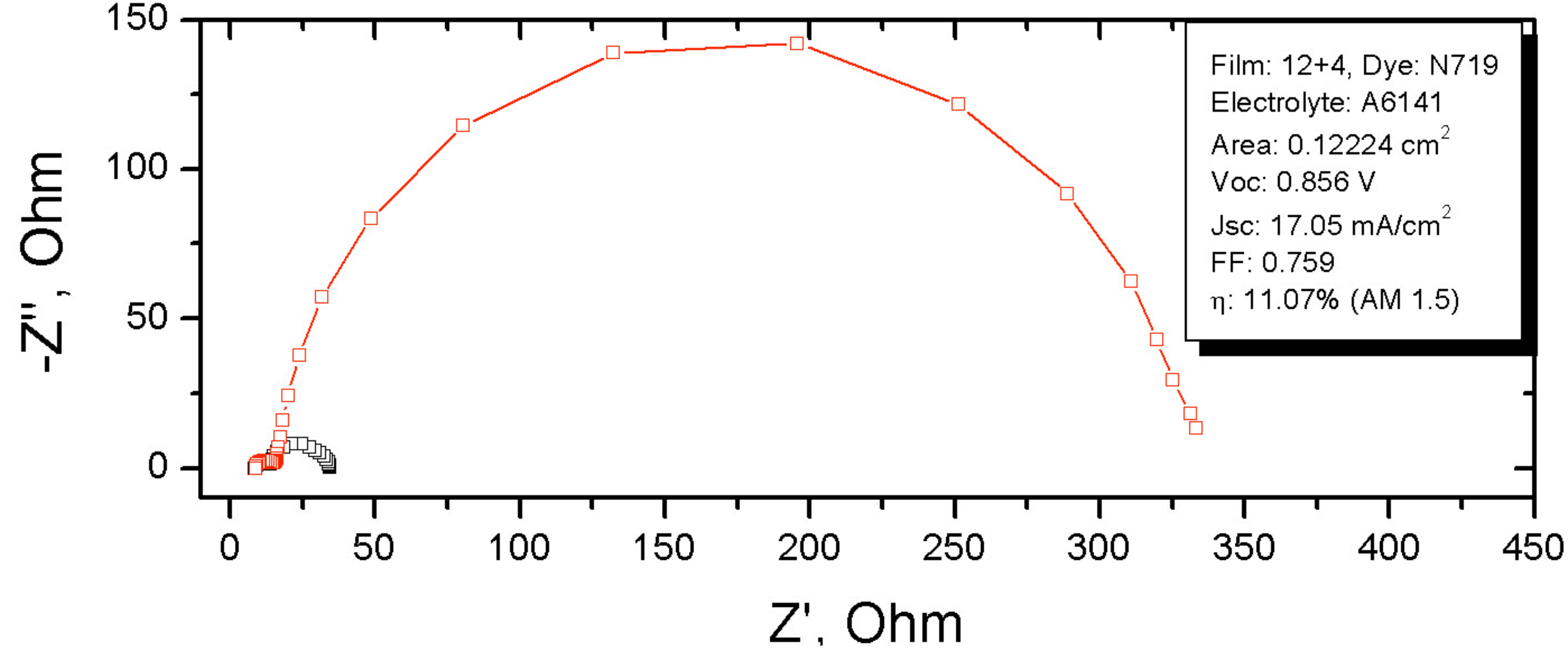
Chemical Capacitance Recombination



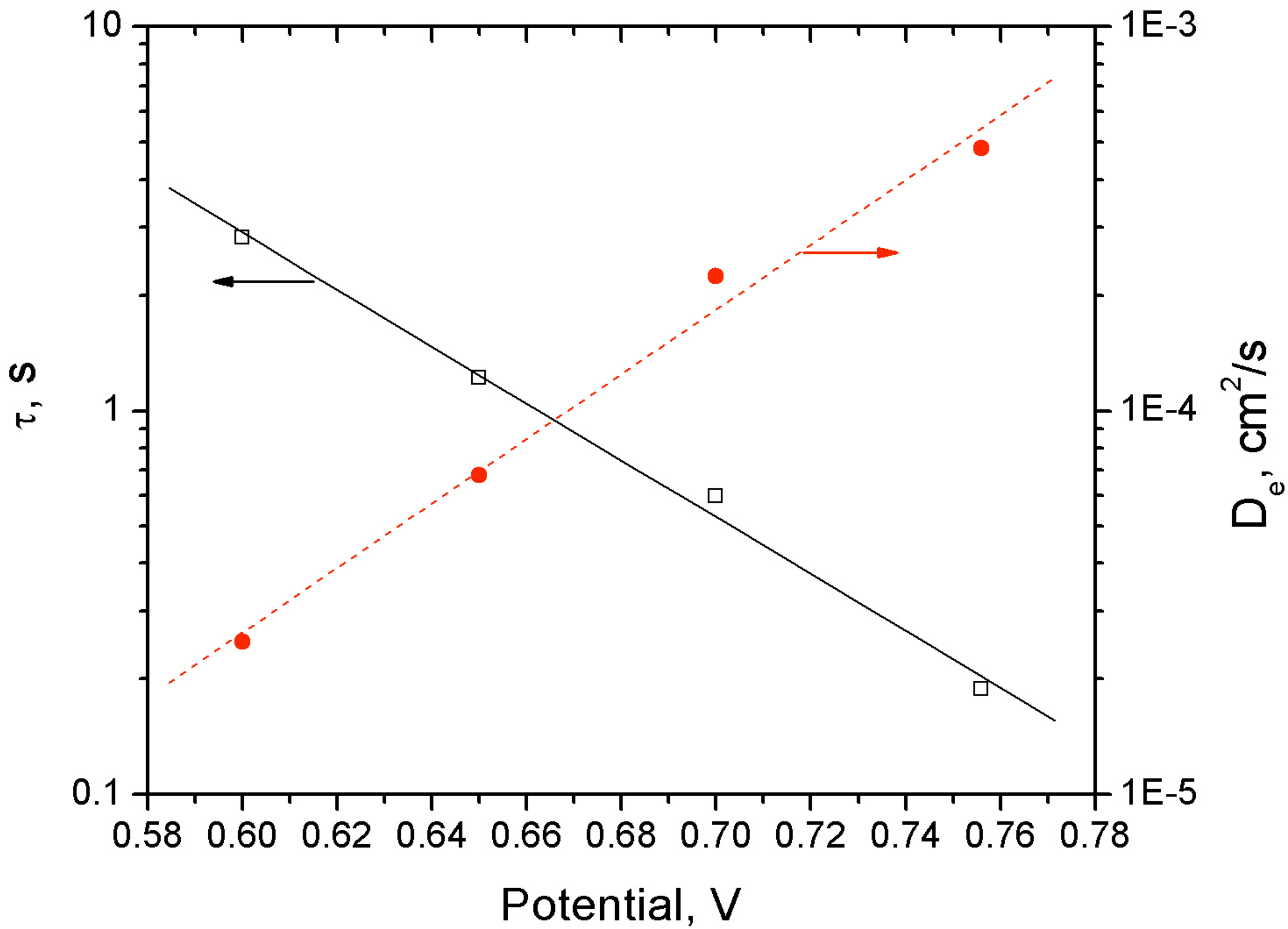
Q Wang, J. Moser and M. Graetzel J.Phys. Chem B in press



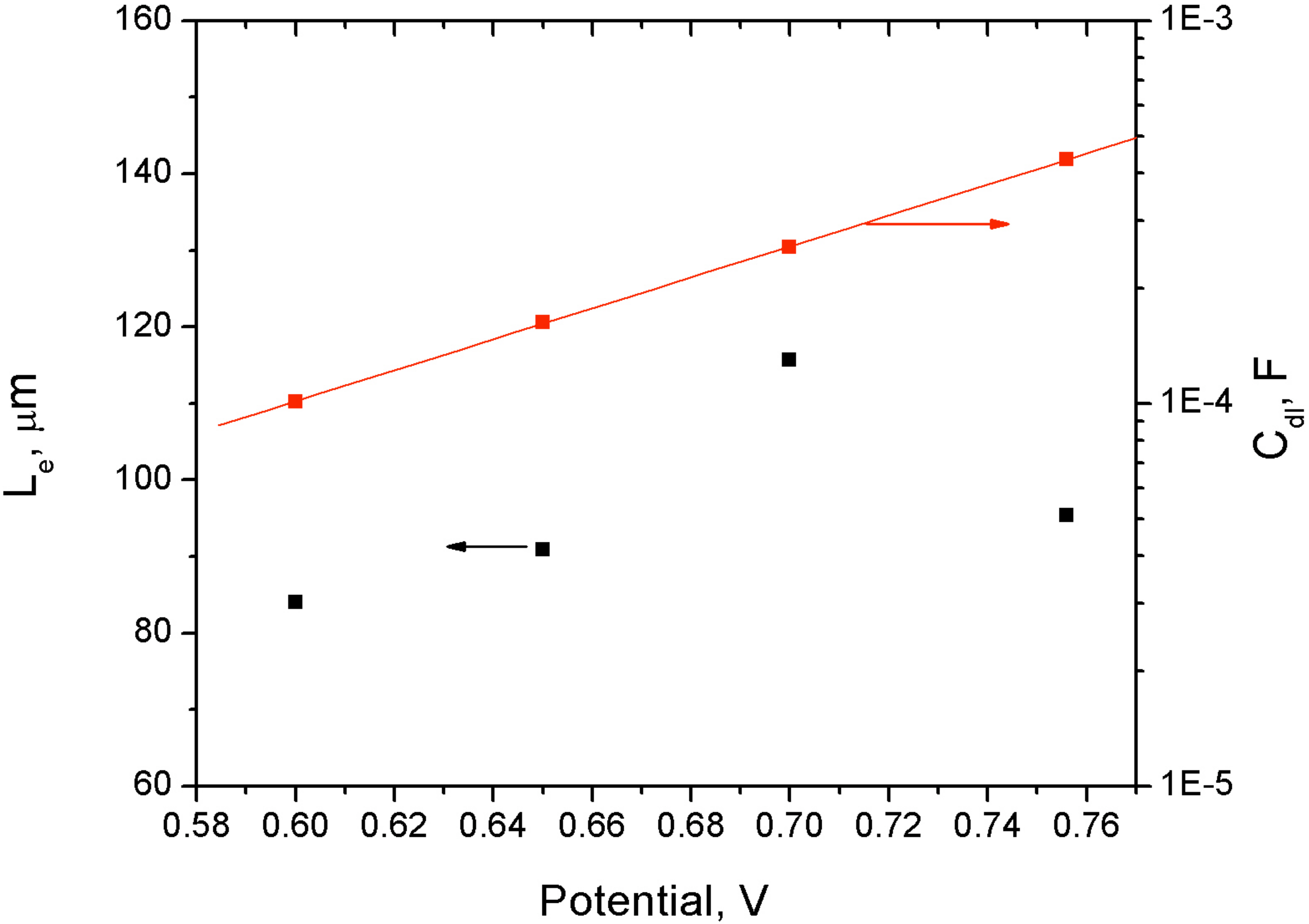
theta
-70
-60
-50
-40
-30
-20
-10
0
0.01
0.1
1
10
100
1000
10000
100000
Frequency, Hz
1 sun, OCV
0.1 sun, OCV



-Z'', Ohm
150
100
50
0
0
50
100
150
200
250
300
350
400
450
Z', Ohm
Film: 12+4, Dye: N719
Electrolyte: A6141
Area: 0.12224 cm2
Voc: 0.856 V
Jsc: 17.05 mA/cm2
FF: 0.759
η: 11.07% (AM 1.5)

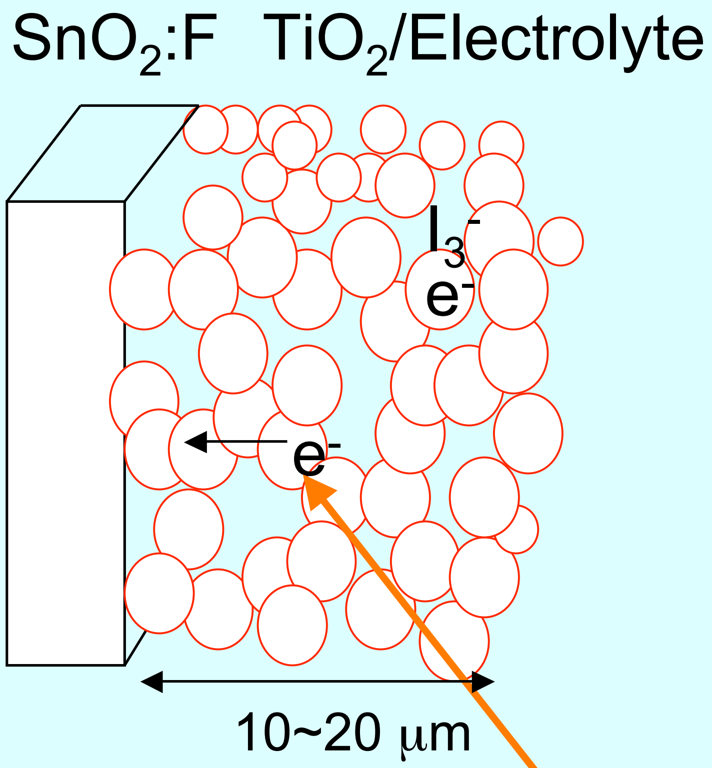


10
1
0.1
1E-3
1E-4
1E-5
0.58
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
0.76
0.78
Potential, V
τ, s
De, cm2/s



160
140
120
100
80
60
1E-3
1E-4
1E-5
0.58
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
0.76
L_e, μm
C_{dl}, F
Potential, V

Electron Transport: Diffusion and Electron Lifetime



$$L = \sqrt{D\tau}$$

Charge recombination

2 e- + I3- = 3I-

Electrons should travel to the SnO_2 before charge recombination occurs

Diffusion length should exceed the thickness of the mesoscopic TiO_2 film

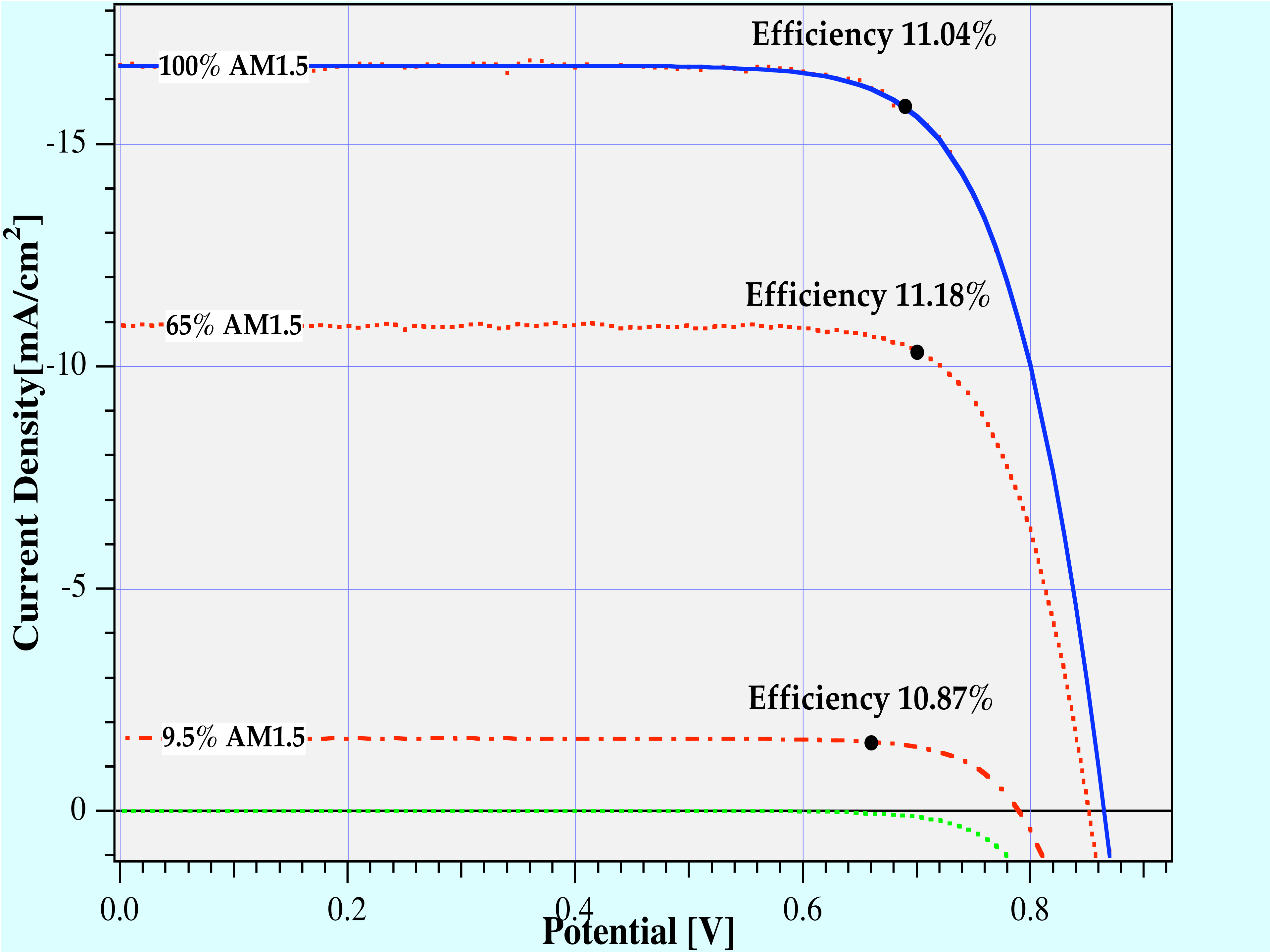
Increasing the injection and lowering the recombination rates is critical for maximizing the open circuit voltage of the cell !

$$V_{oc} = (nRT/F)\ln(K\Phi/(k_1[S^+] + k_2[D^+]))$$

$K\Phi$: charge carrier photo-generation rate

k_1, k_2: recombination rate constants

n: ideality factor of the junction


Efficiency 11.04%
100% AM1.5
Efficiency 11.18%
65% AM1.5
Efficiency 10.87%
9.5% AM1.5
Current Density[mA/cm2]
-15
-10
-5
0
0.0
0.2
0.4
0.6
0.8
Potential [V]

STABILITY

Requirements for outdoor use according to international PV standards applied to single crystal silicon but so far not to thin film PV cells

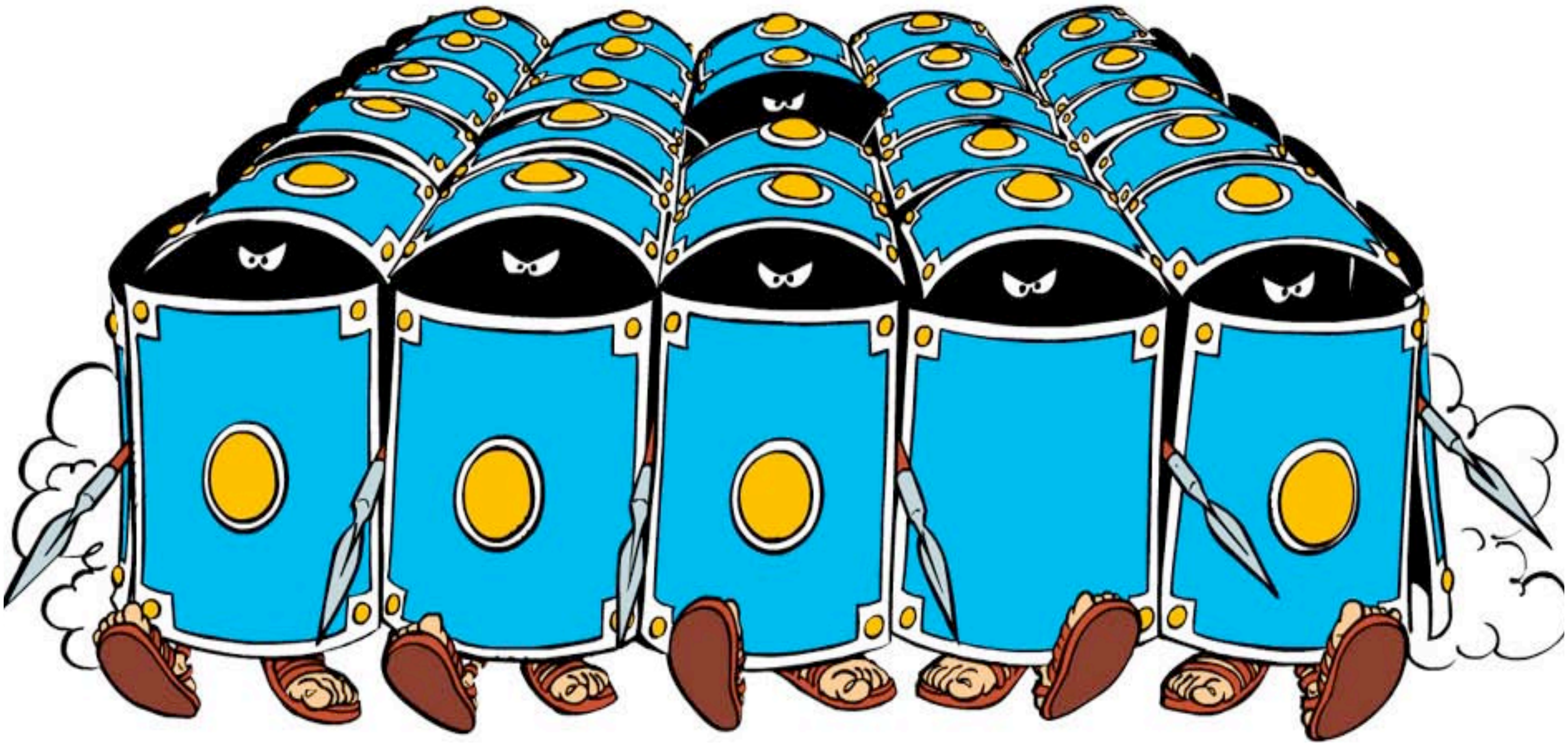
UV plus heat (55-60 C): 1000 hours

Accelerated thermal test at 85 C: 1000 h

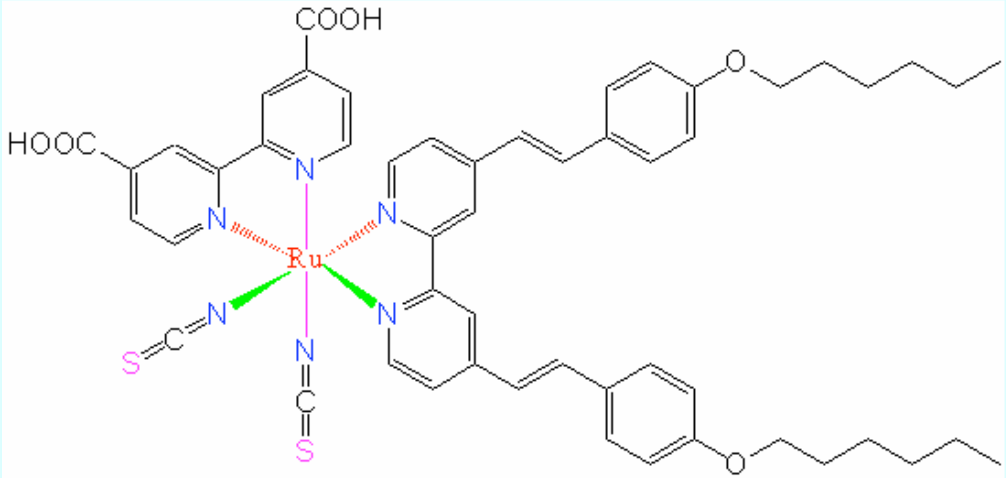
Humidity test and temperature cycling (sealing issues)

Self-assembly of stable and well defined monomolecular layers of sensitizer at the interface provides long term photovoltaic stability and high conversion efficiency

Interface Engineering in Dye-Sensitised Solar Cells

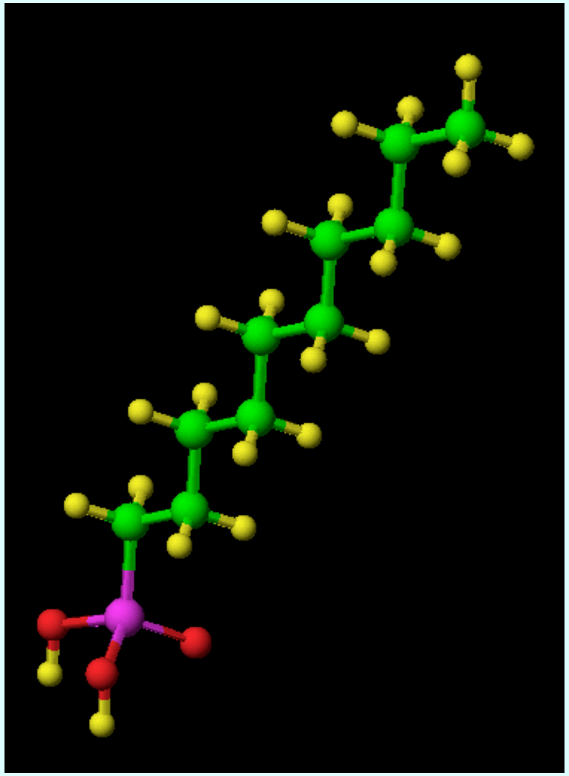


K-19



Photoanode: 8+5

Decylphosphonate



ROBUST Electrolyte

PMII: 0.8 M

I_2: 0.15 M

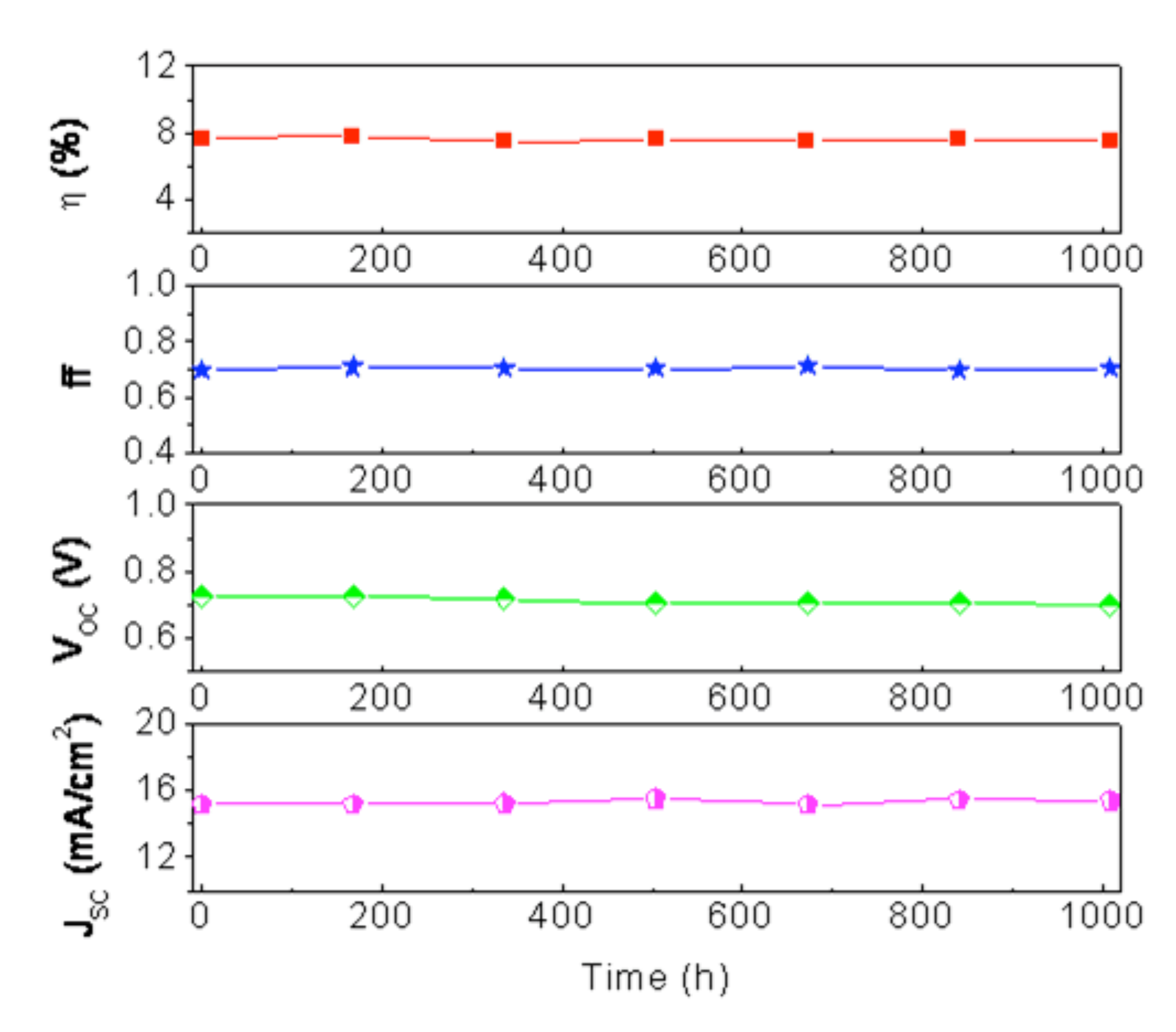
NMBI: 0.5 M

0.1 M GSCN

MPN solvent

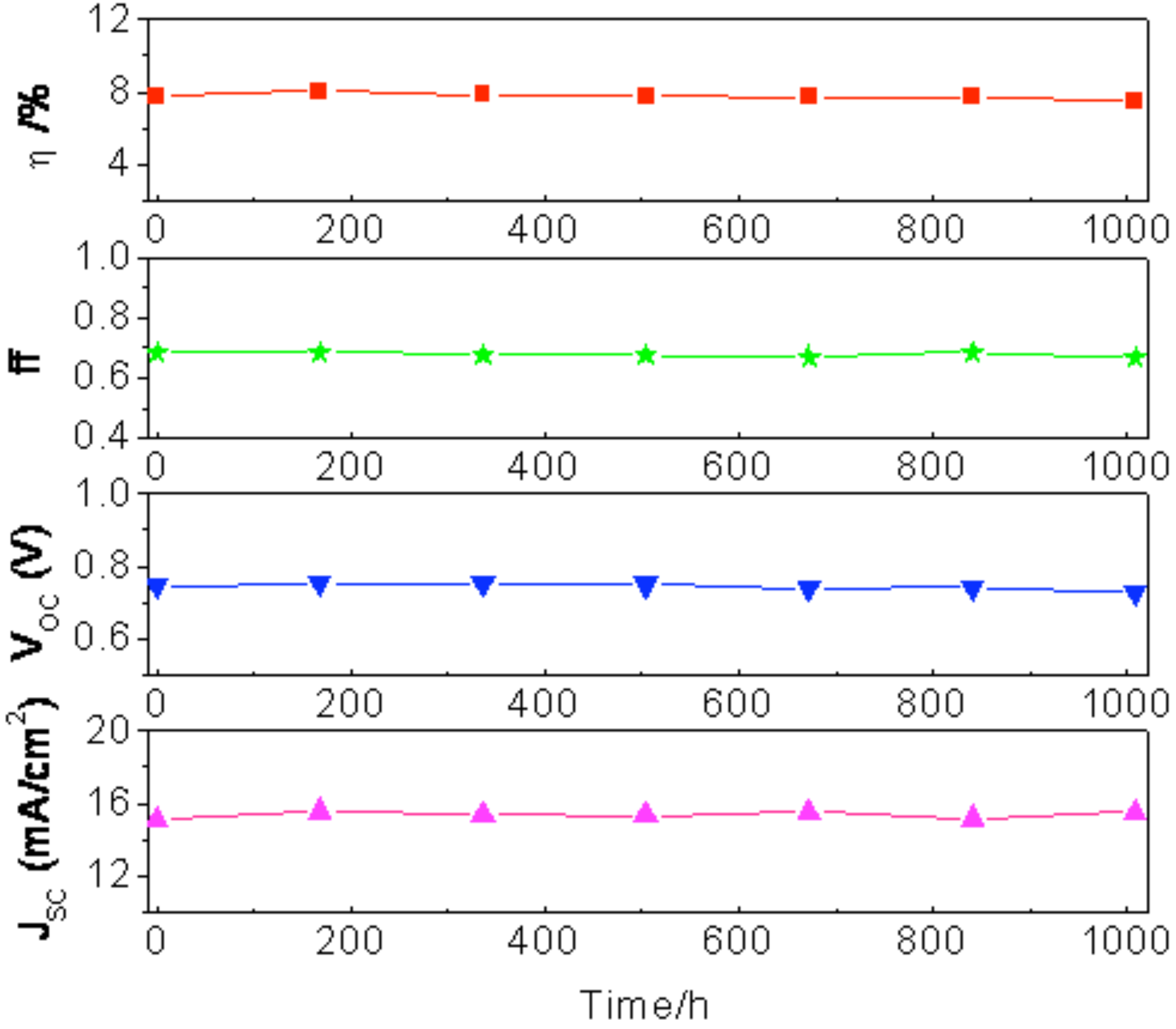
Efficiency: > 8.0%

80 °C evolution of device parameters in the dark



Wang, P.; Klein, C.; Humphry-Baker, R.; Zakeeruddin, S. M.; Grätzel, M. Appl. Phys. Lett. 2005, 86. 123508.

60 °C evolution of device parameters under one sun soaking



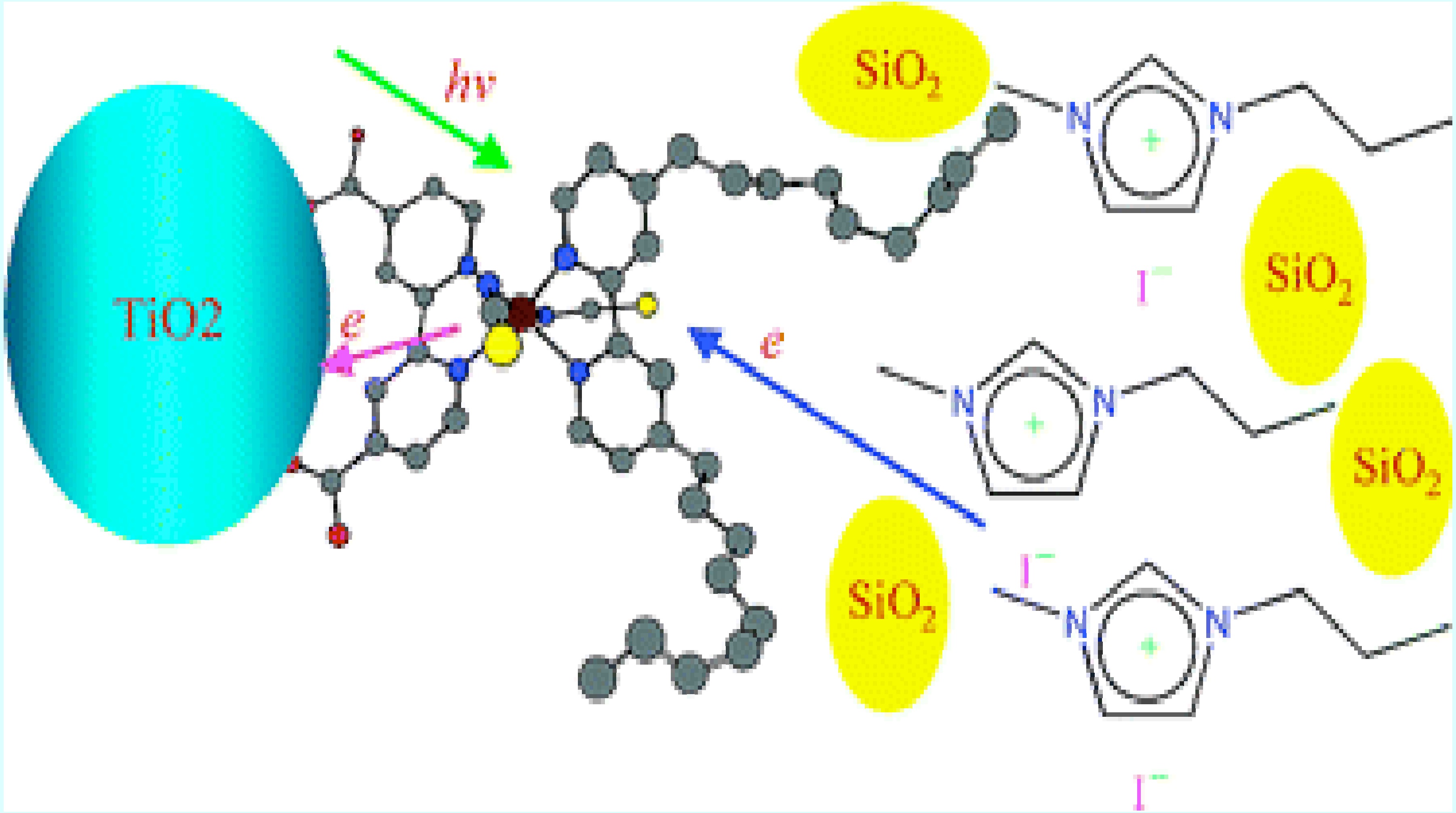
SOLVENT-FREE SYSTEMS

SOLID (POLYMER)ELECTROLYTES,

SOLIDIFIED IONIC LIQUIDS

HOLE CONDUCTORS

Ionic solid electrolytes

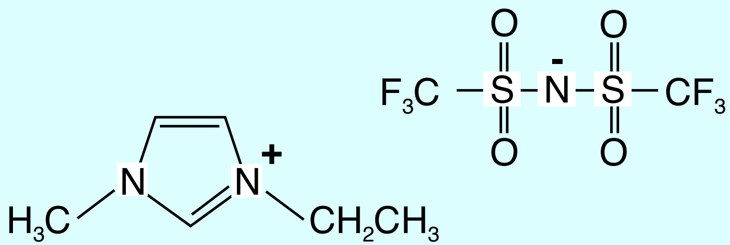


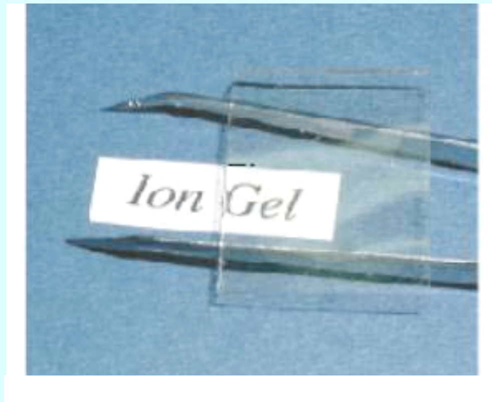
P. Wang, S.M. Zakeeruddin, P. Comte, I. Exnar, and M. Grätzel
Peng Wang et al *J. Am. Chem. Soc* 2003, 125, 1166-1167

ION-GEL Electrolyte (NEDO)

Features of Ionic Liquids

- Consists of only Ions
- Liquid under wide temp. range　ex. -10℃ to 400℃
- non volatile
- Chemically stable and non combustible
- High electronic conductivity





1-Ethyl-3-methylimidazolium - Bis(trifluoromethylsulfonyl) Amide

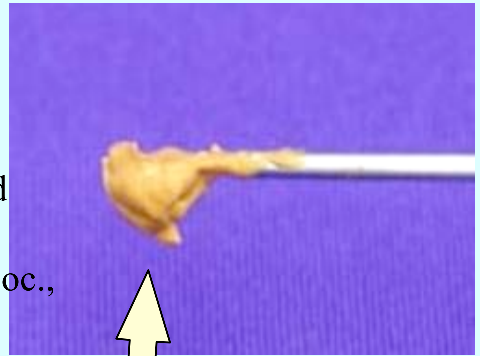
EMIm-TFSA

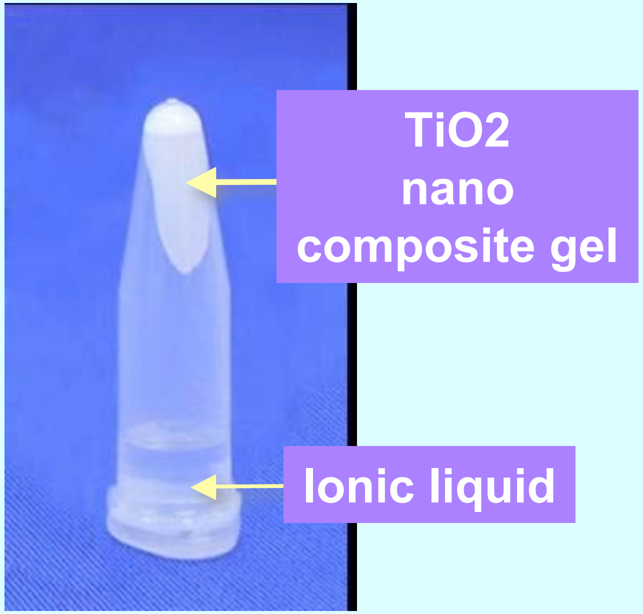
Nano composite Ion Gel

References

(1) T.Fukushima, A.Kosaka, Y.Ishimura, T.Yamamoto, T.Takigawa, N.Ishii and T.Aida, Science, 27(2003)2072.

(2) P.Wang, S.M.Zakeeruddin, P.Comte, I.Exnar and M.Graetzel, J.Am.Chem.Soc., 125(2003)1166





EMIm-TFSA + TiO_2 (P25, 10 wt%)

Centrifugal separation 2000 G (6400 rpm) x 1hr

I_2 content

Influence of Nano Particles

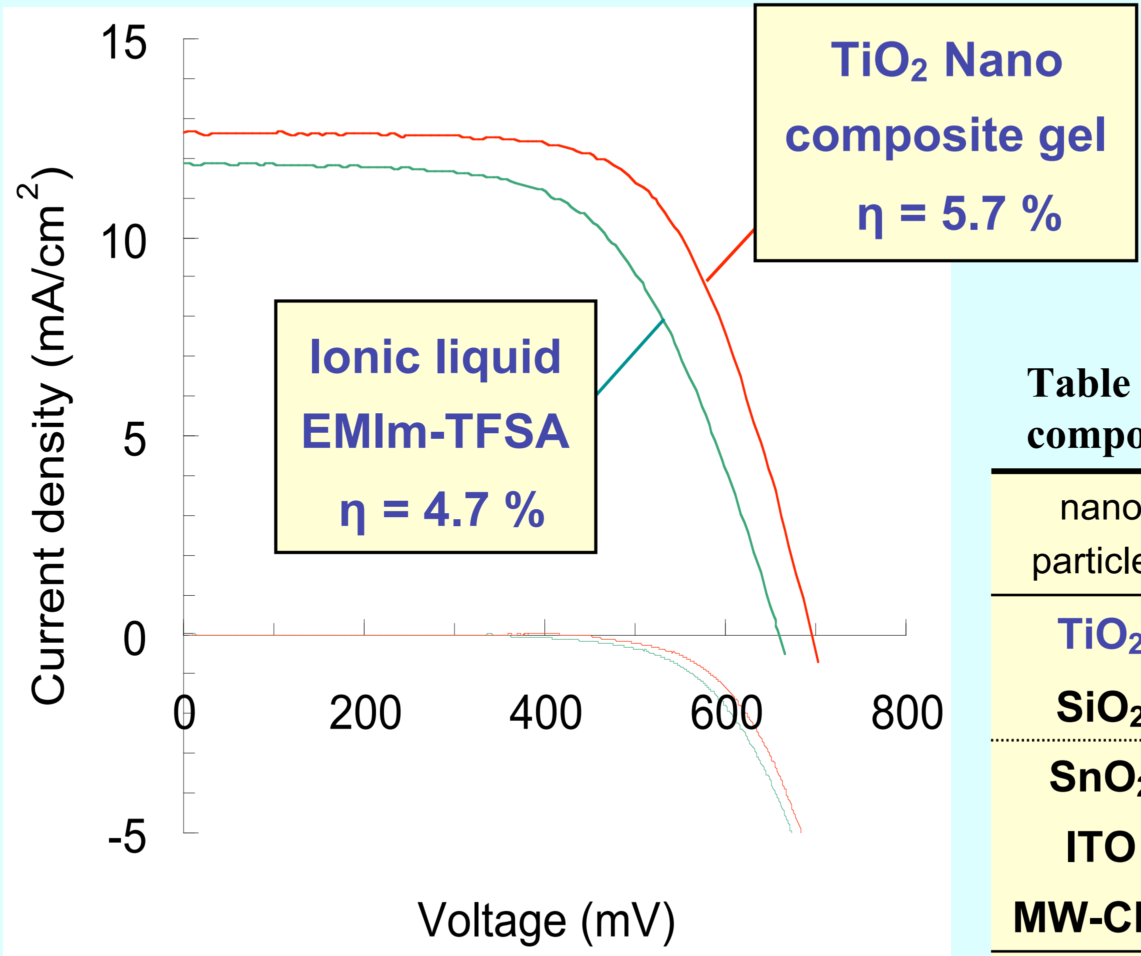


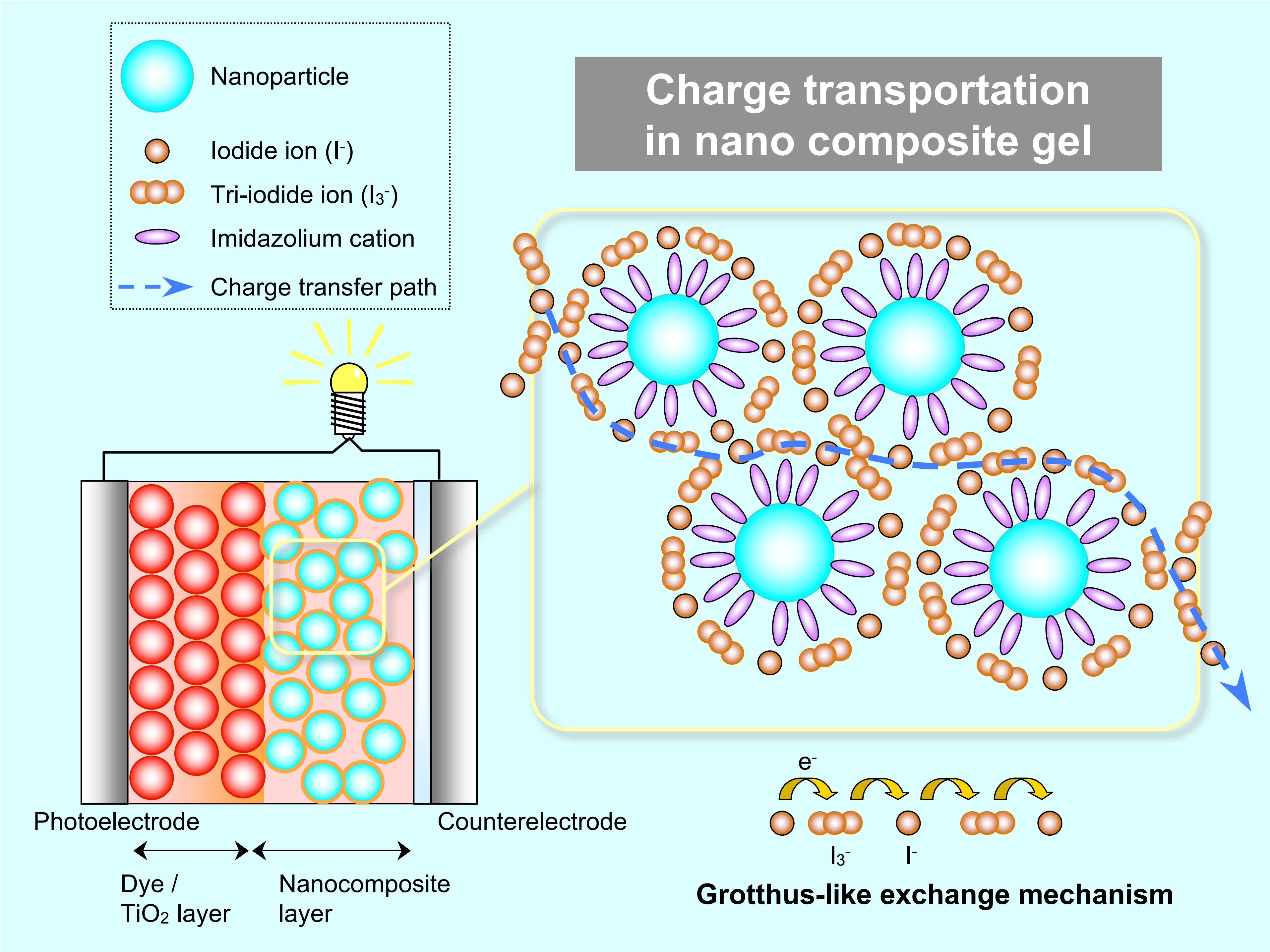
Fig. I-V characteristics of nano composite ion gel cell and bare ionic liquid cell

TiO_2 (P25); anatase, 28 nm

Table PV performance of nano composite ion gel cells

nano particles	J_{sc} (mA/cm²)	V_{oc} (mV)	FF	η (%)
TiO_2	12.5	696	0.65	**5.7**
SiO_2	12.5	719	0.64	**5.8**
SnO_2	12.1	679	0.61	**5.0**
ITO	12.5	685	0.60	**5.1**
MW-CNT	12.0	706	0.57	**4.8**
without particles	11.8	661	0.60	**4.7**

Courtesy of Dr. Nobuo Tanabe Fujikura Ltd


Nanoparticle
Iodide ion (I^-)
Tri-iodide ion (I_3^-)
Imidazolium cation
Charge transfer path
Charge transportation in nano composite gel
Photoelectrode
Counterelectrode
Dye / TiO_2 layer
Nanocomposite layer
e^-
I_3^-
I^-
Grotthus-like exchange mechanism

Latent gel electrolyte precursors for quasi-solid dye sensitized solar cells

Takehito Kato, Akio Okazaki and Shuzi Hayase* Chem.Commun. 2005,363-365

Received (in Cambridge, UK) 12th August 2004, Accepted 23rd September 2004
First published as an Advance Article on the web 29th November 2004
DOI: 10.1039/b412462f

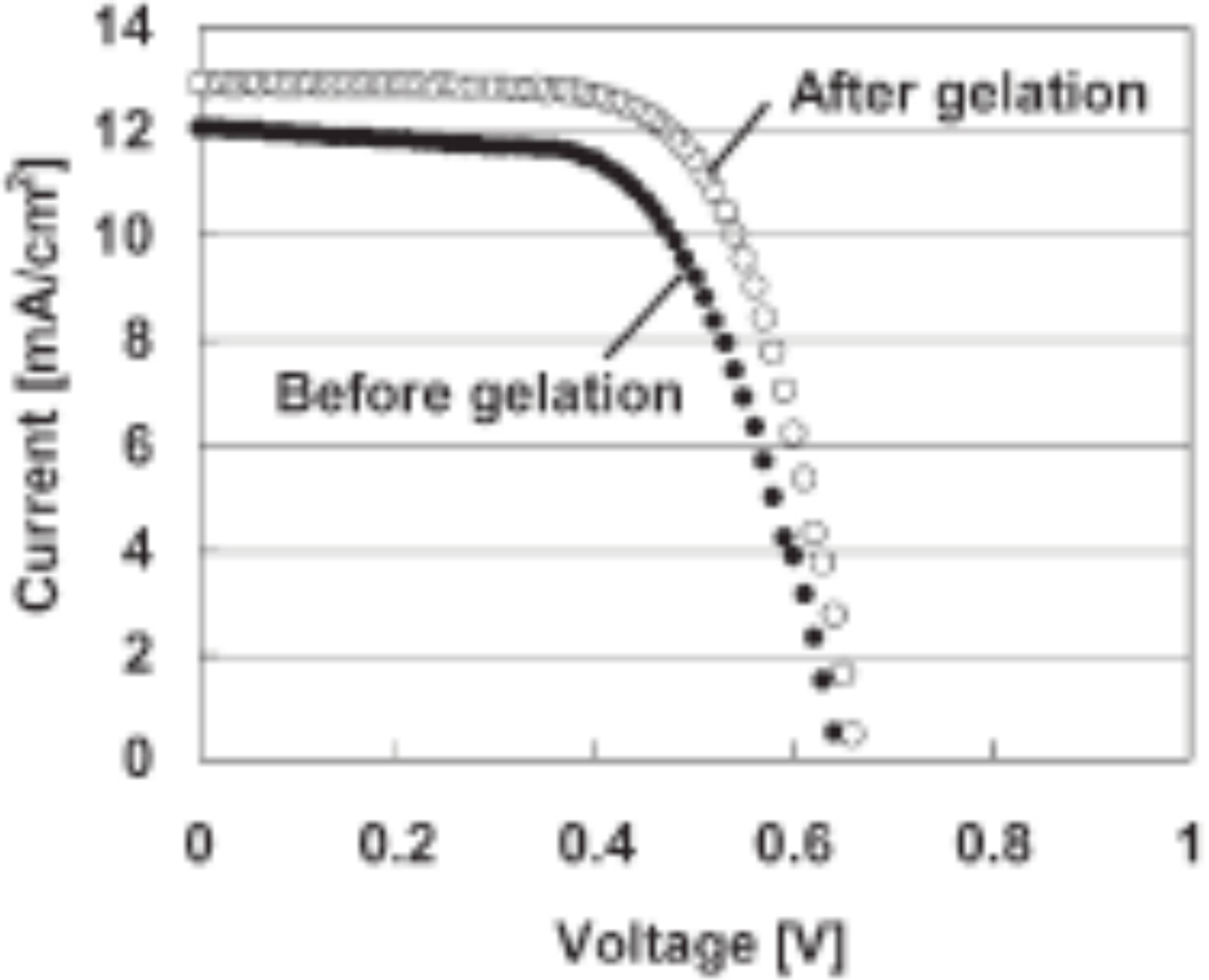
New latent chemically-cross-linked gel electrolyte precursors for quasi-solid dye sensitized solar cells (QDSC) are reported. The gel electrolyte precursors consist of nano-particles and dicarboxylic acids as the latent gelators. The viscosity of the precursor is low at first and does not increase during storage at room temperature. However, when the precursor is baked at 80 °C, it solidifies immediately. Photo-voltaic performance is maintained after solidification.

Dye sensitized solar cells (DSC) contain volatile liquid electrolytes.[1] Therefore, achieving solidification is one of the crucial research areas: all-solid DSCs have been reported previously.[2–10]

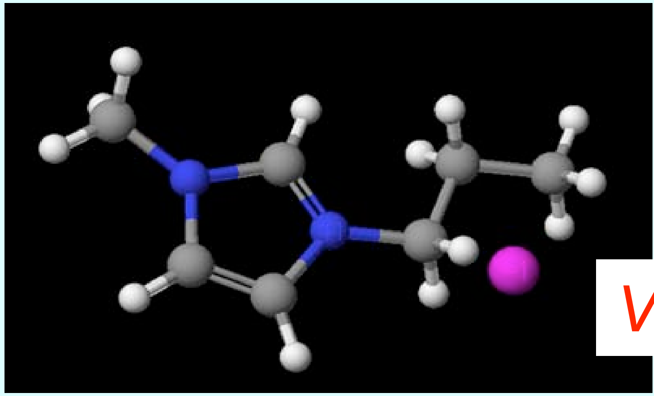
Table 1 Summary of gel electrolyte precursors and their compositions

Abbreviation[a]	Electrolyte TS3[b]	Nano-particle[c]	Dicarboxylic acid	Gelation?
Pregel-C6-300	100	3	3	No[d]
L-Gel-Pre-C12-300	100	3	3	Yes
L-Gel-Pre-C16-300	100	3	3	Yes

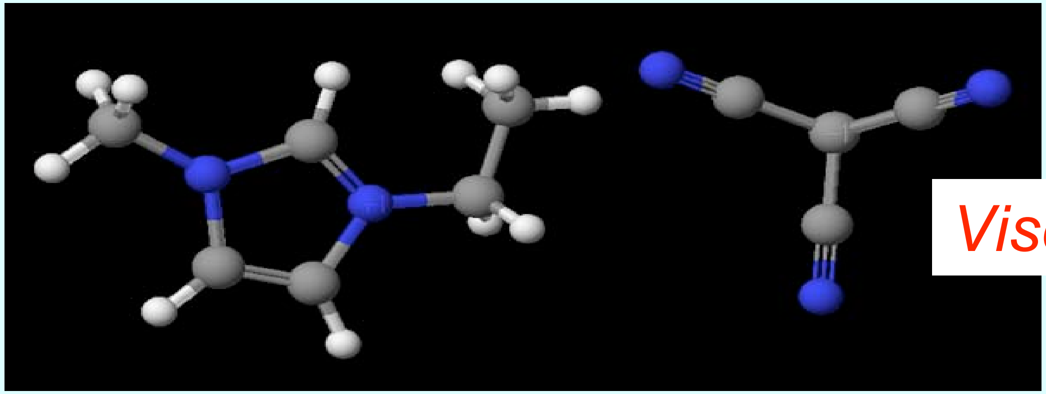
[a] C6: $HOOC(CH_2)_4COOH$, C12: $HOOC(CH_2)_{10}COOH$, C16: $HOOC(CH_2)_{14}COOH$. [b] Electrolyte (TS3): MePrImI (containing 5% water), I_2 300 mM, *t*-BuPy 580 mM, LiI 500 mM. [c] AEROSIL 300 (Nippon Aerosil). [d] After a swift reaction, precipitation occurred.



14
12
10
8
6
4
2
0
Current [mA/cm²]
0
0.2
0.4
0.6
0.8
1
Voltage [V]
After gelation
Before gelation

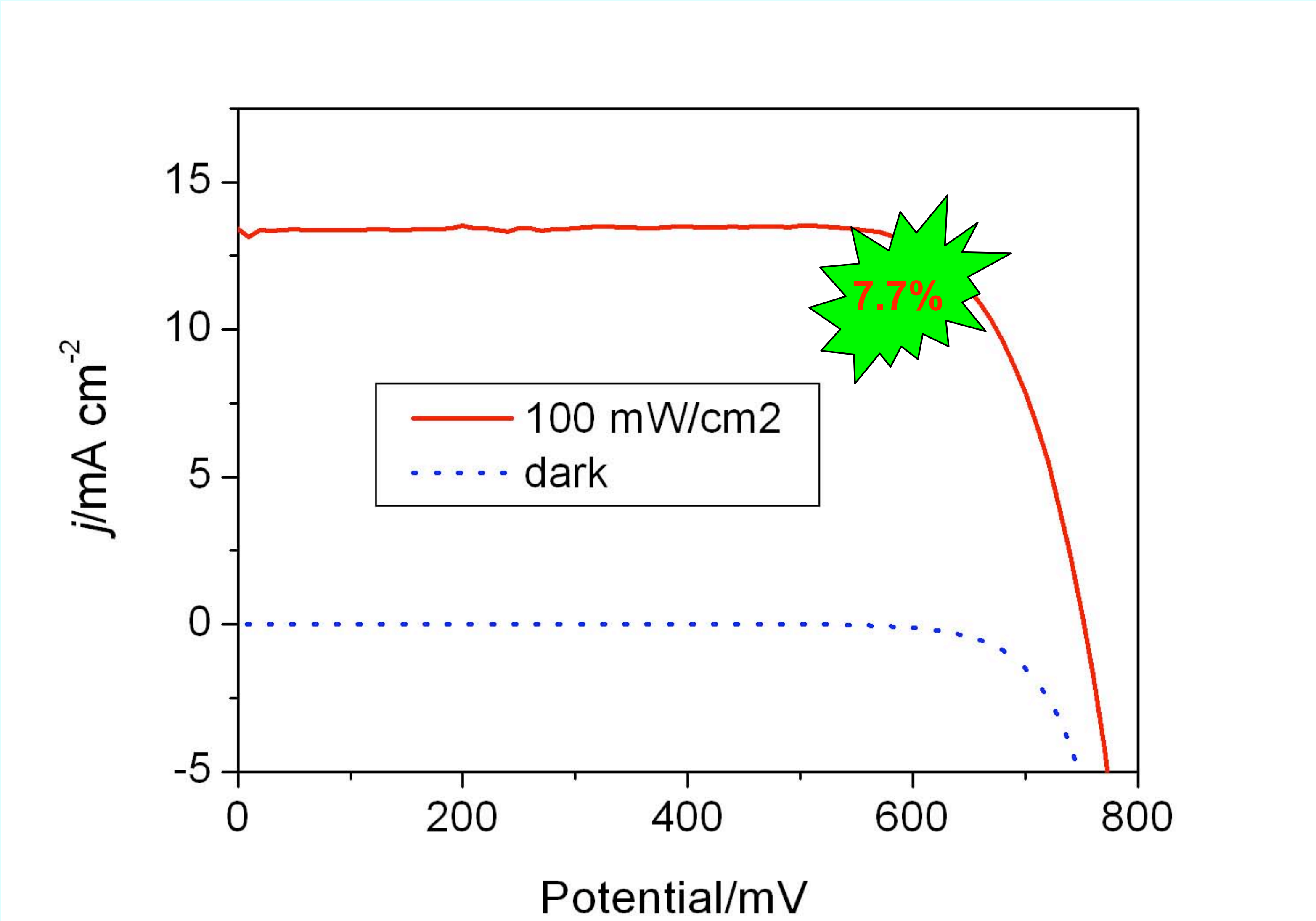


Viscosity: 900 cp at 22 ^{o}C



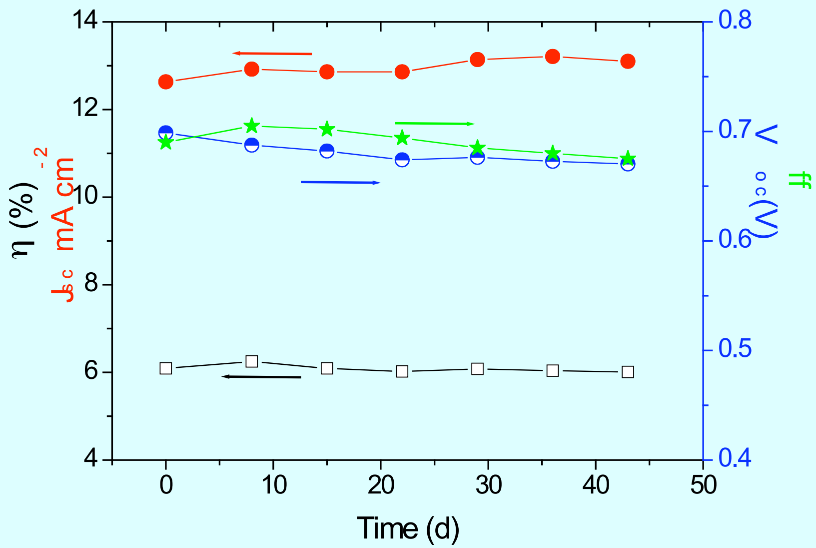
Viscosity: 18 cp at 22 ^{o}C

Photovoltaic performance



Wang, P.; Klein, C.; Humphry-Baker, R.; Zakeeruddin, S.M. and Grätzel.M. *J. Am. Chem Soc.* 2005, 127, 808.

Evolution of device parameters using quasi-solid ionic liquid gel electrolyte under one Sun light soaking at *60 °C*



PMII/EMINCS: 65:35 (volume)

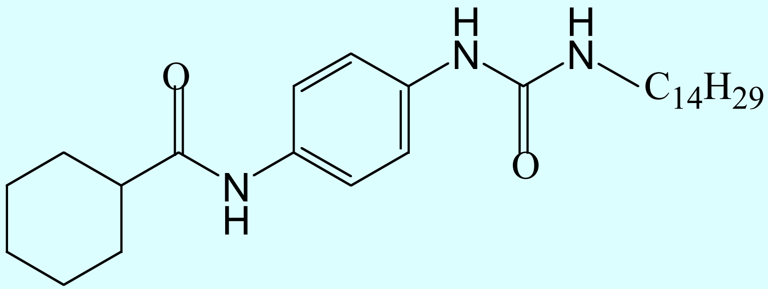
I_2: 0.2 M

NMBI: 0.5 M

GuNCS: 0.1 M

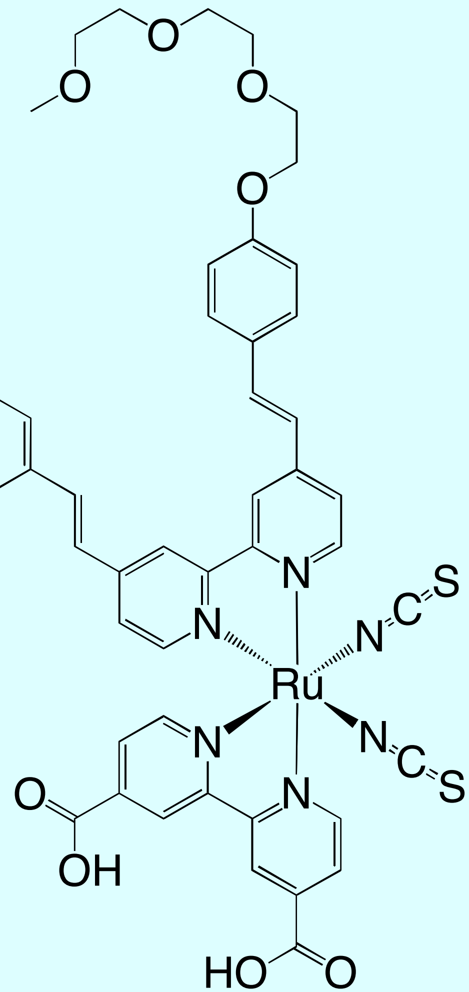
Gelator: 2 wt %

Gelator

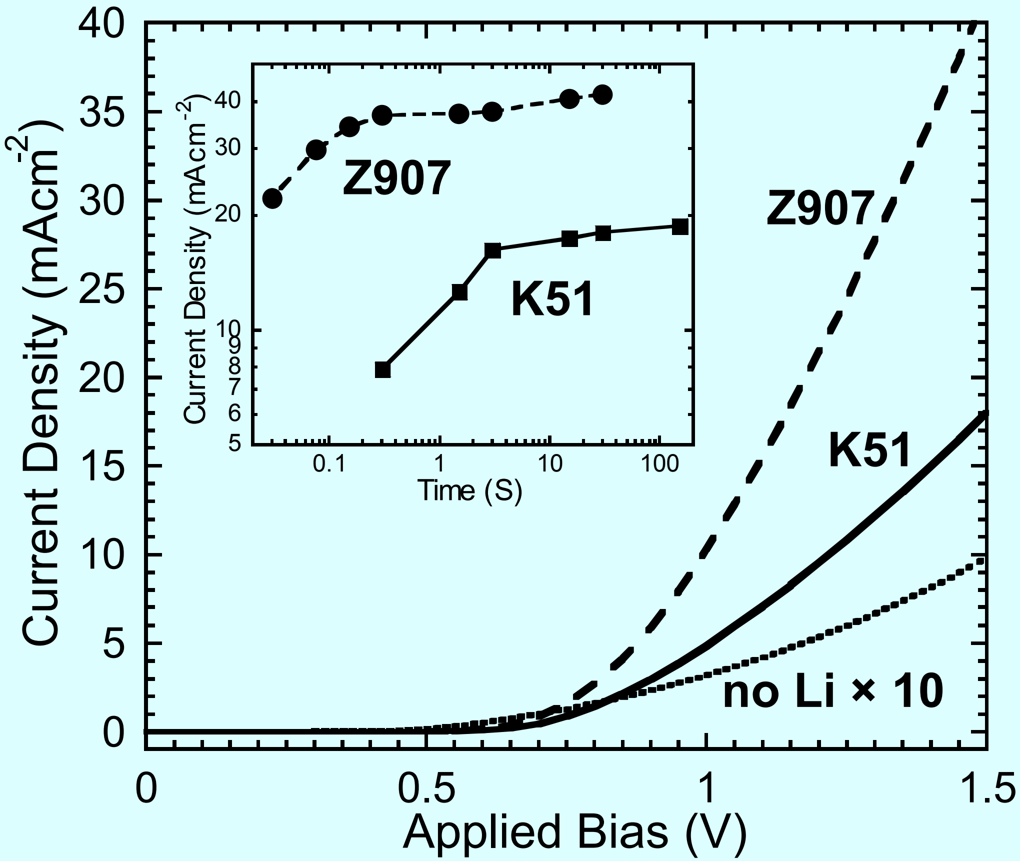


Dye K19+DPA

Ion coordinating sensitizers



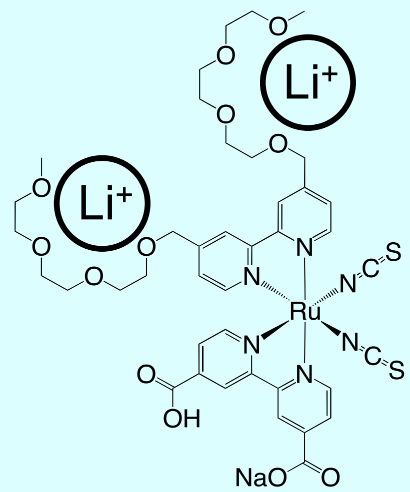
Immobilization of Li Ions



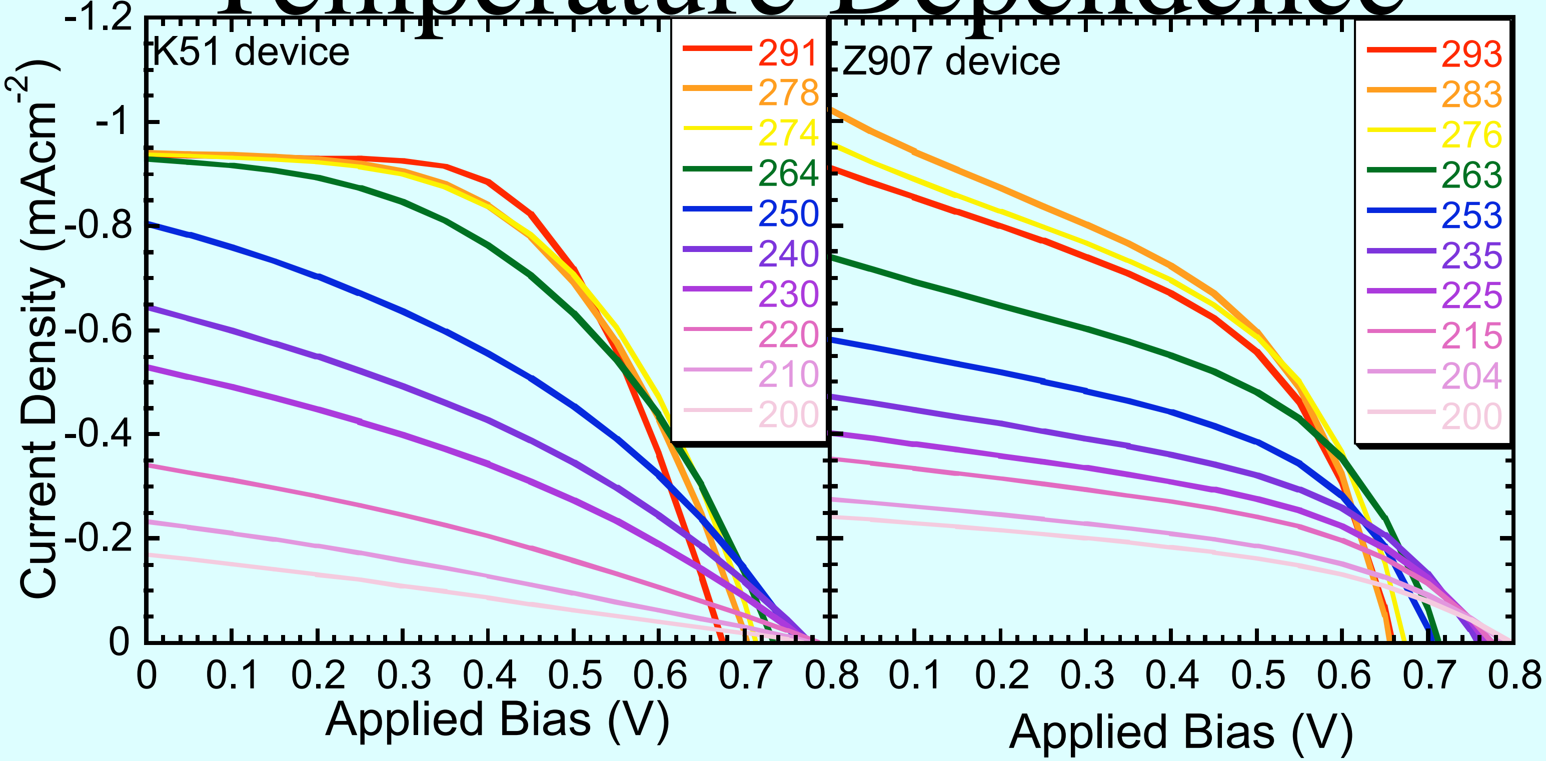
Li hugely increases *J* density

No longer space-charge limited current.

K51 immobilizes ions on dye backbone.



Temperature Dependence

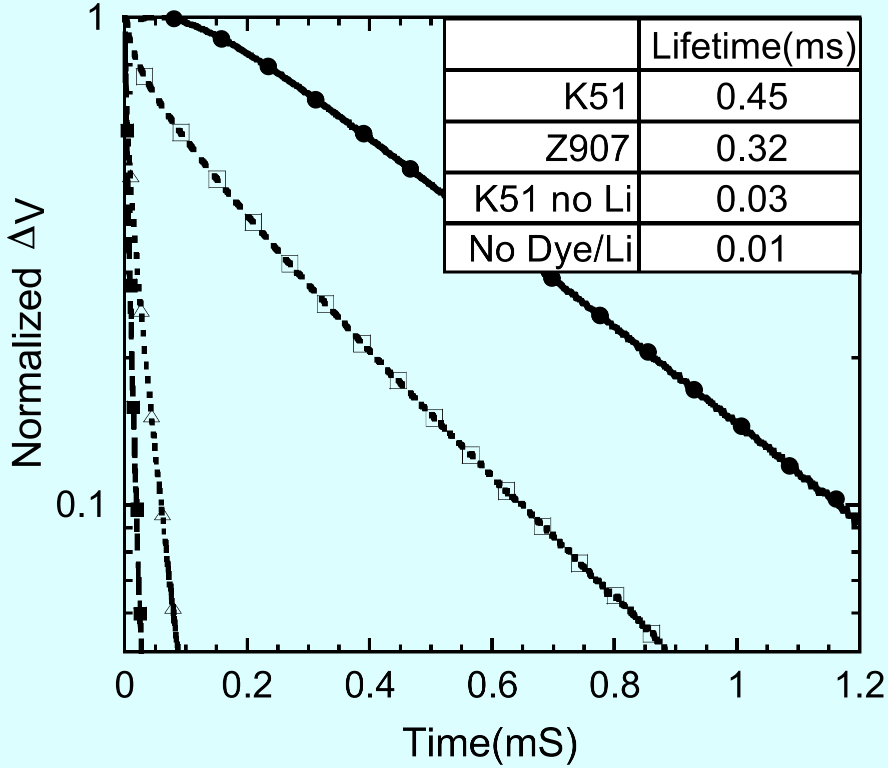


Increased charge mobility with temperature ↑ current and fill factor

Increased charge recombination ↓ voltage and current

For K51 ↑ mobility wins. For Z907 ↑ charge recombination wins

Transient Voltage Decay's



PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2005; **13**:333–340
Published online 18 April 2005 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/pip.631

Research

SHORT COMMUNICATION: ACCELERATED PUBLICATION

Dye Solar Cells Without Electrolyte or Hole-transport Layers: a Feasibility Study of a Concept Based on Direct Regeneration of the Dye by Metallic Conductors

F. O. Lenzmann[1*†], B. C. O'Regan[1], J. J. T. Smits[2], H. P. C. E. Kuipers[2], P. M. Sommeling[1], L. H. Slooff[1] and J. A. M. van Roosmalen[1]
[1]*ECN, Solar Energy, Westerduinweg 3, 1755 LE Petten, The Netherlands*
[2]*Shell Global Solutions, Badhuisweg 3, CM 1031 Amsterdam, The Netherlands*

Flat structures consisting of dense dye-sensitized TiO_2 films with various materials for dye regeneration (TiO_2/dye/regeneration material) are compared. Au and PEDOT:PSS were tested as metal or metal-like regeneration materials and compared with reference compounds, such as the redox couple I^-/I_3^- in solution and p-type CuSCN. Under the exclusion of TiO_2 bandgap excitation, the short-circuit photocurrent densities for the various structures differ by less than ~30%, suggesting comparable charge separation efficiencies. The good performance of a metallic regeneration material implies, that the frequently assumed requirement of p-type or 'hole conducting' properties for the regeneration material in solid state dye solar cells is questionable. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: dye-sensitized solar cells; solid state; Au; hole transport layer

1. INTRODUCTION

The development of dye sensitized solar cells[1] over the past years has resulted in improved long-term stability[2] and increased efficiency. Currently, the highest certified efficiency values are 11·0% for small liquid junction type laboratory cells (0·25 cm^2) and 8·2% on larger cell areas (2·36 cm^2).[3,4] Recent progress in device manufacturing indicates that this technology is approaching maturity for market introduction.[5]

* Correspondence to: Frank O. Lenzmann, ECN, Solar Energy, Westerduinweg 3, 1755 LE Petten, The Netherlands.
† E-mail: lenzmann@ecn.nl

Contract/grant sponsors: Shell Research Foundation; EZ.
Contract/grant sponsor: European Commission; contract/grant number: SES6-CT-2003-502620.

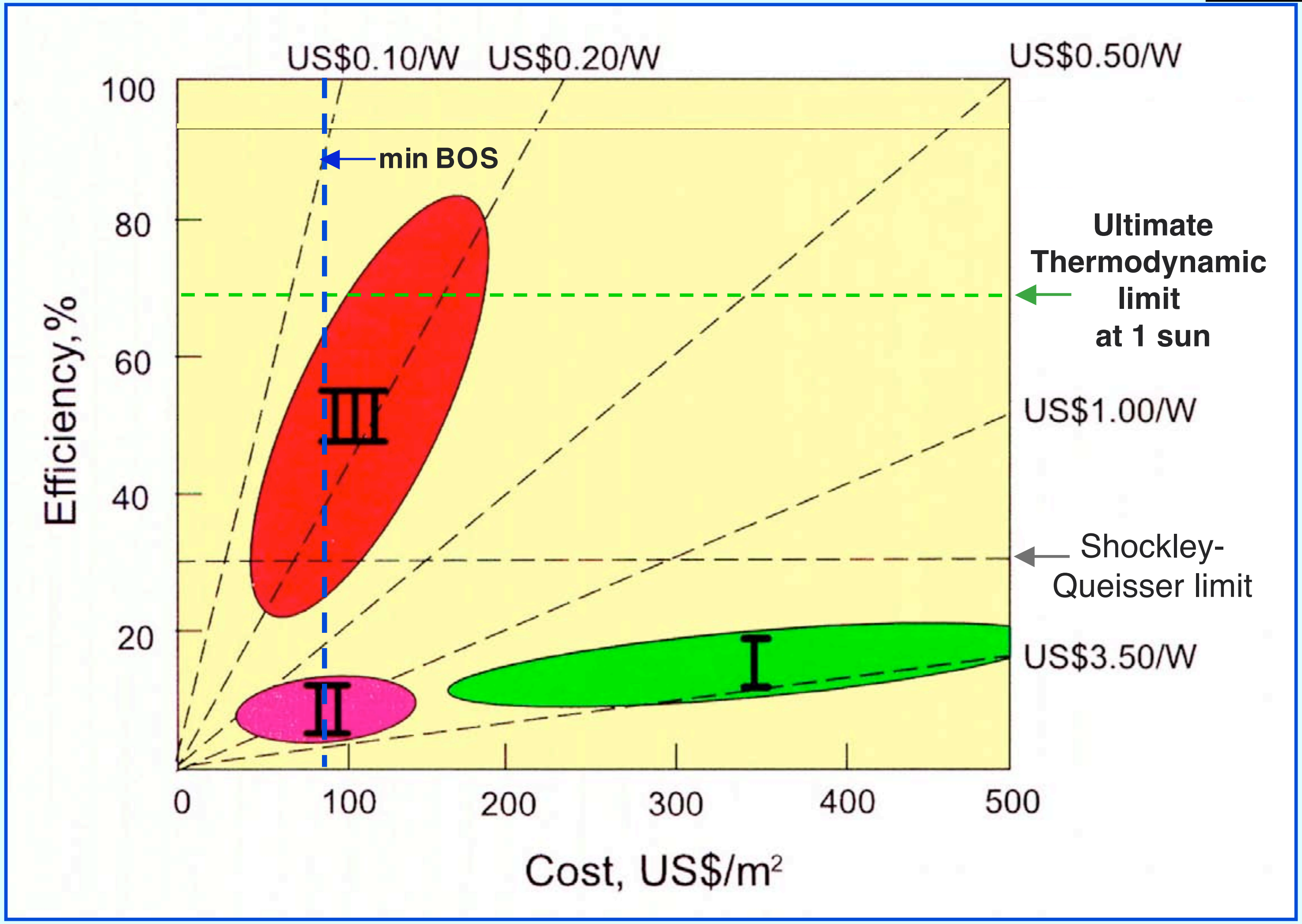
Received 20 December 2004
Revised 16 February 2005

Advantages *vs*. Silicon Cells

- **Low cost and ease of production**
- **Performance increases with temperature narrowing the efficiency gap**
- **Bifacial configuration - advantage for diffuse light and albedo**
- **Efficiency less sensitive to angle of incidence**
- **Transparency for power windows**
- **Color can be varied by selection of the dye, invisible PV-cells based on near-IR sensitizers are feasable**
- **Low energy content (for silicon this is 5 GJ/m2 !), payback time is only a few months as compared to years for silicon.**
- **Outperforms amorphous Si**

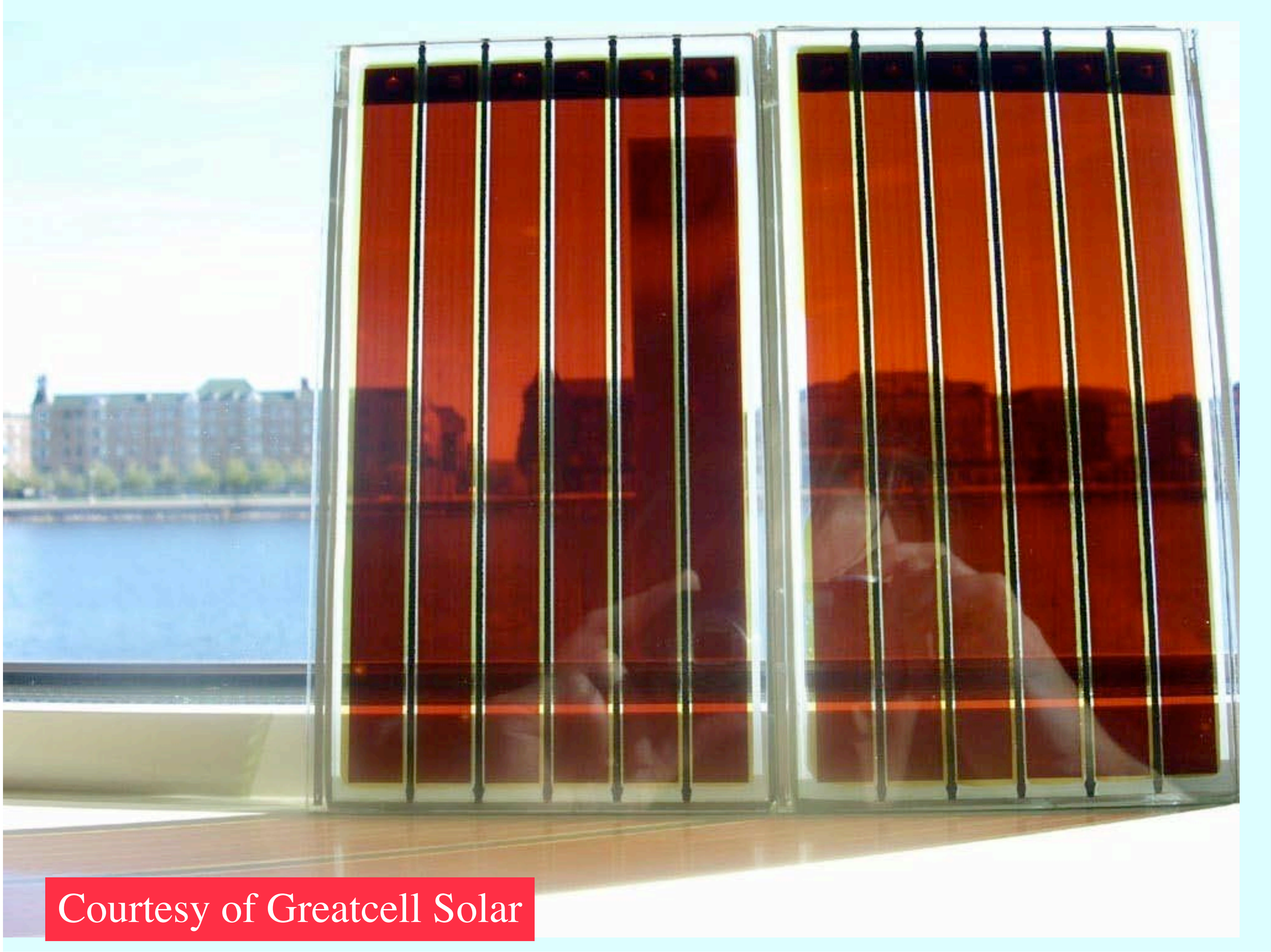
PV Power Costs as Function of Module Efficiency and Cost

From Martin Green

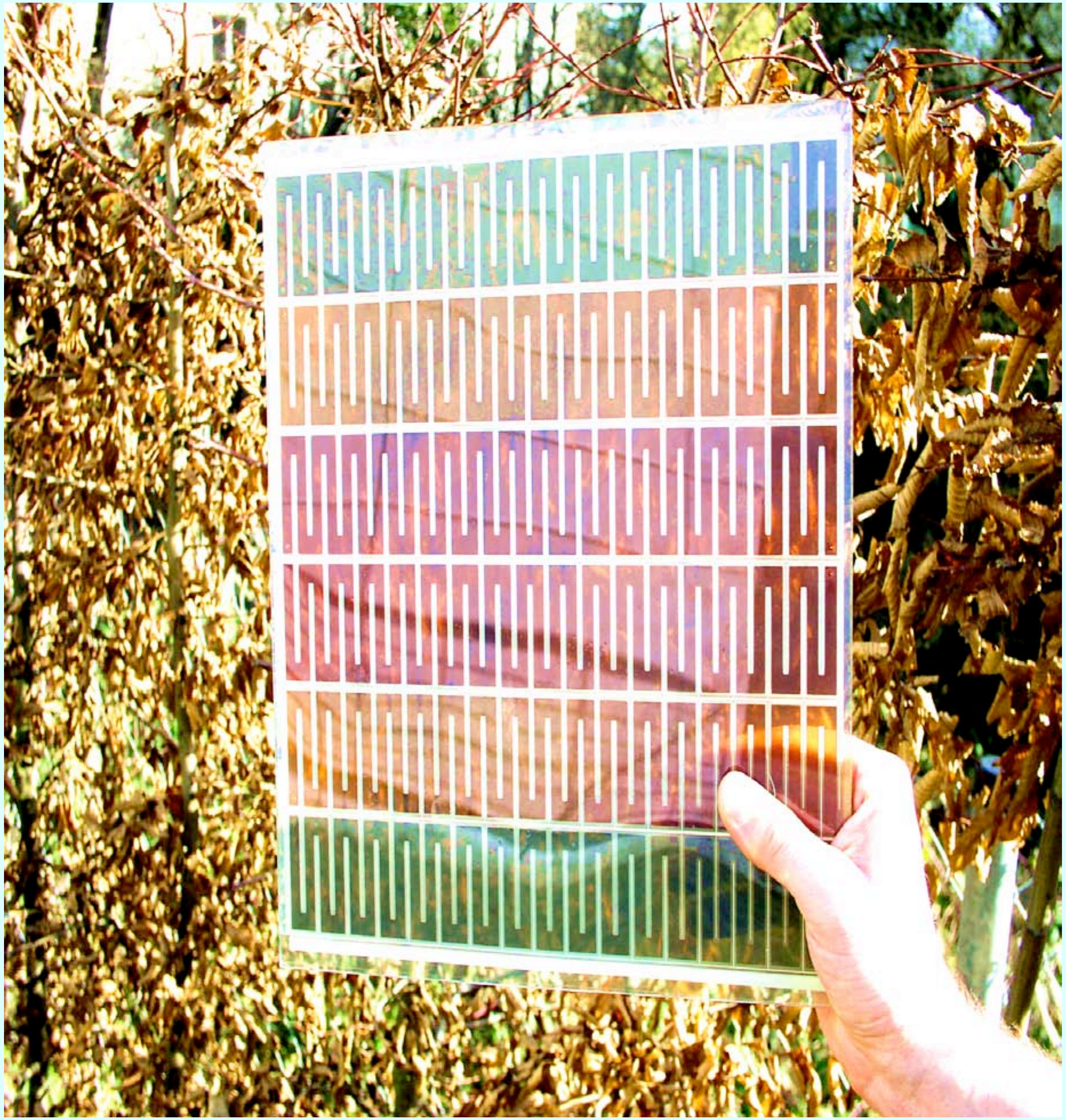


For PV to provide the full level of C-free energy required for electricity and fuel—solar power cost needs to be ~5 cents/kWh ($1.00 W_p)


Konarka®

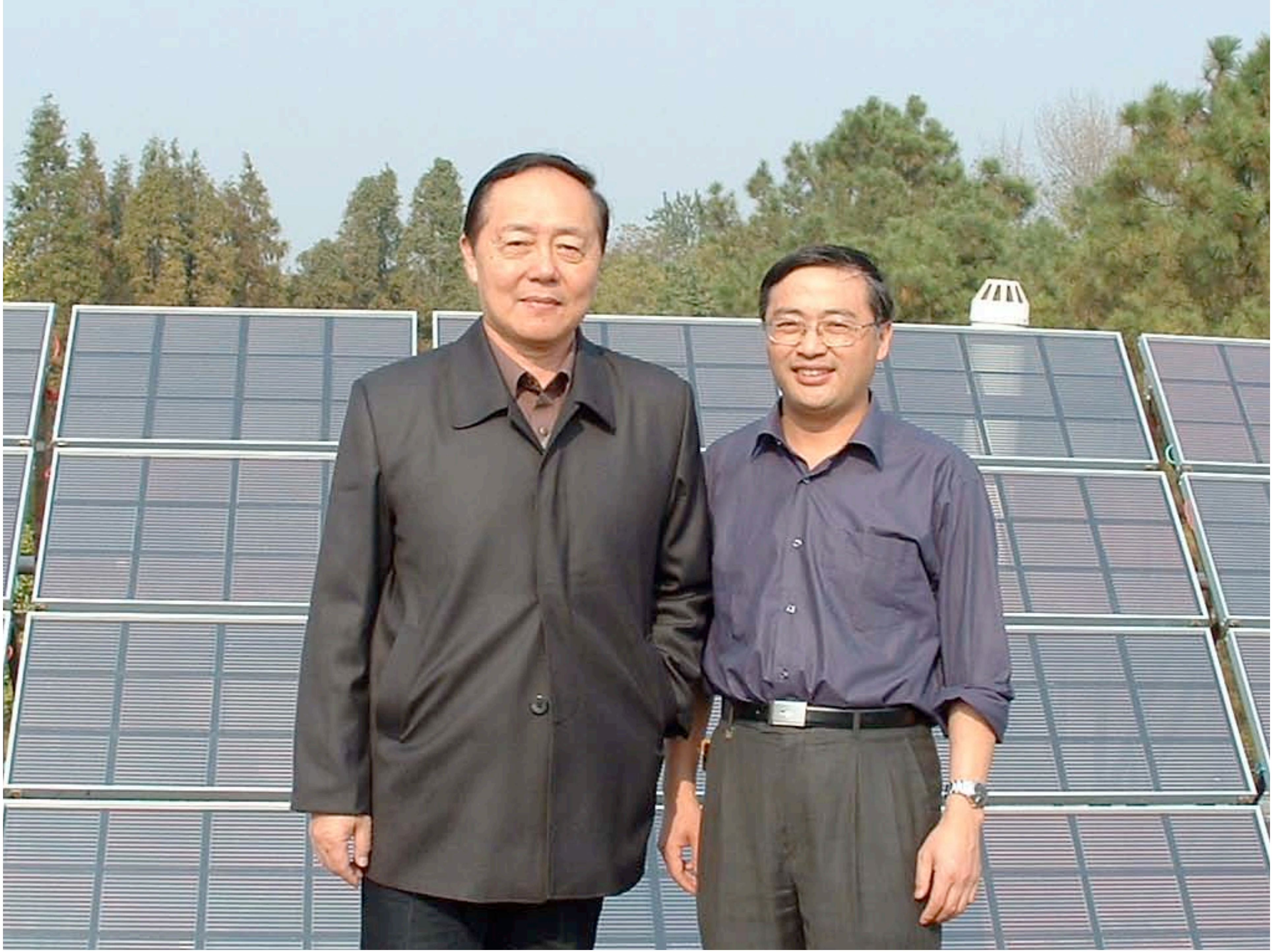

Courtesy of Greatcell Solar

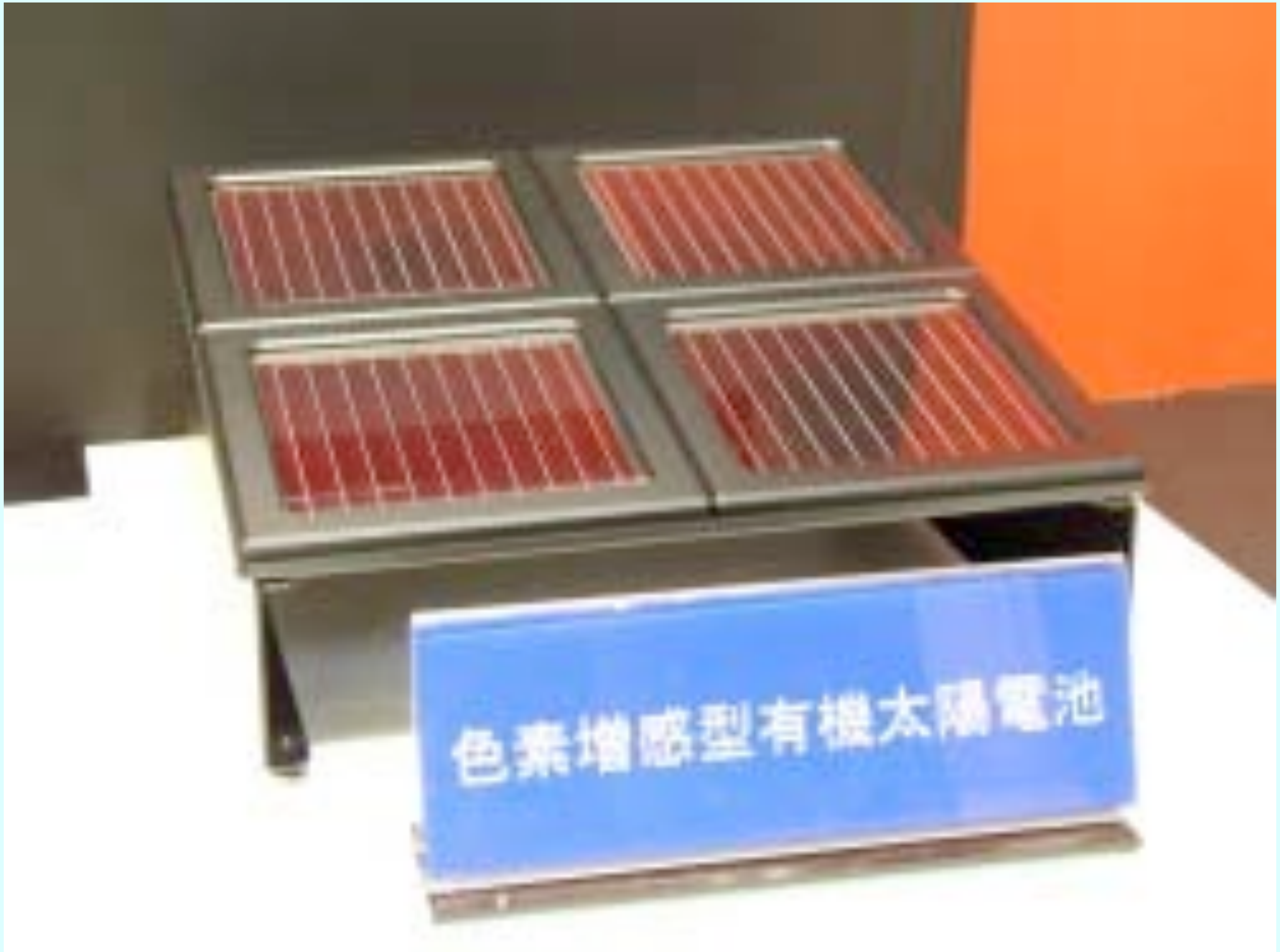
Various colours in a series-connected dye solar cell module



Courtesy Dr. Winfried Hoffman, CEO, RWE, SCHOTT Solar GmbH


ETRI





Hitachi's new dye sensitized cell achieves 9.3 percent efficiency


色素増感型太陽電池
AISIN
消火器


O2
H2
cogene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クリーンな エアコン。
温水
廃熱
電気
室内エアコン
家庭内の家電
FUEL CELL COGENERATION SYSTEM
わが家では、電気もお湯も
水素と酸素からつくる。
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新しい太陽電池。


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GROUP


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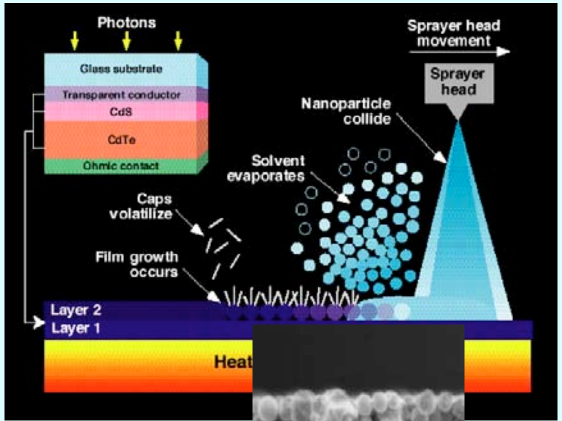
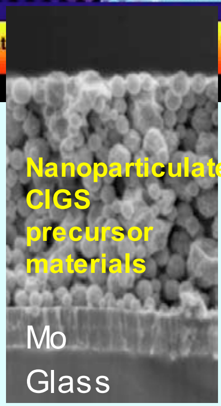
DSC
made by
AISIN -SEIKI
http://www.toyota.co.jp/jp/news/04/Dec/nt04_1204.html

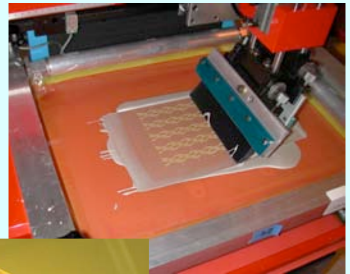
Future Generation PV Technologies

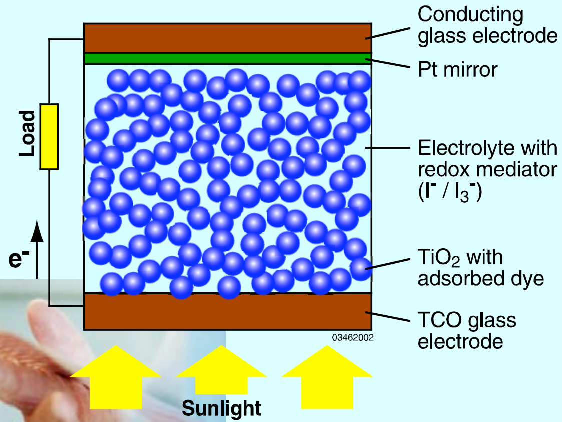
From T. Surek

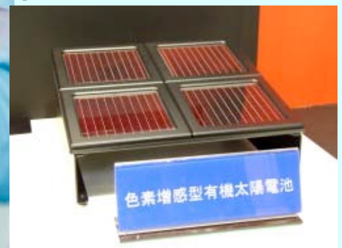
- Opportunities for innovation– ultra low cost, ultra high efficiencies, new materials, new chemistry,new physics
- Photoelectrochemistry
- Excitonic cells (dye cells, semiconducting polymers, molecular semiconductors)
- Quantum dot cells; hot-carrier and impurity band cells; photon tailoring

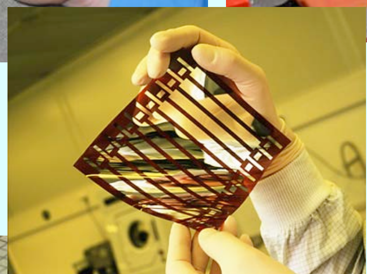


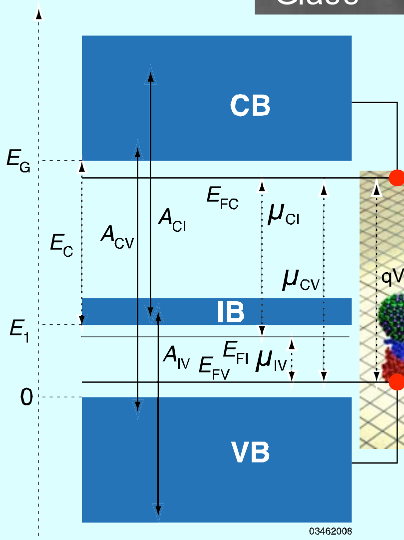


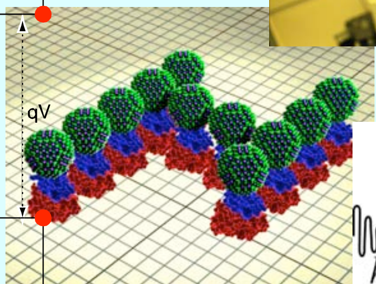


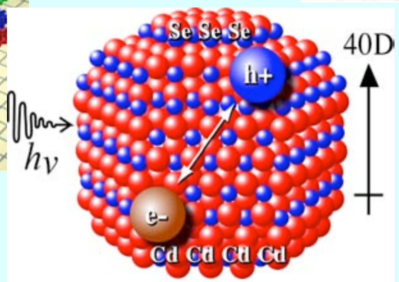


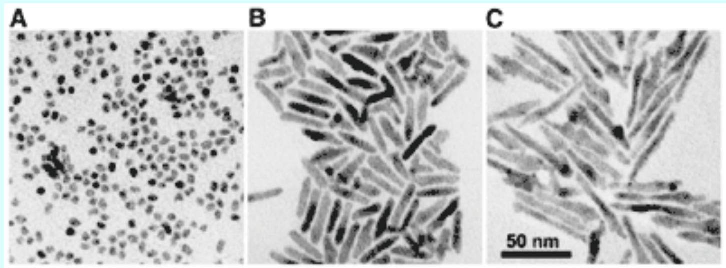


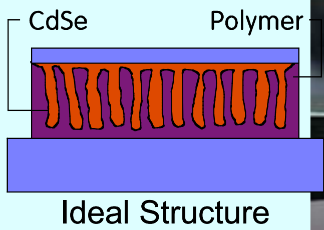












Can laptops run on spinach ?

Spinach photosynthetic power can create electricity.

Integration of Photosynthetic Protein Molecular Complexes in Solid-State Electronic Devices
Rupa Das, Patrick J. Kiley, Michael Segal, Julie Norville, A. Amy Yu, Leyu Wang, Scott A. Trammell, L. Evan Reddick, Rajay Kumar, Francesco Stellacci, Nikolai Lebedev, Joel Schnur, Barry D. Bruce, Shuguang Zhang, and Marc Baldo
Nanoletters 2004, vol 4, pp 1079 - 1083;