Solar Cells

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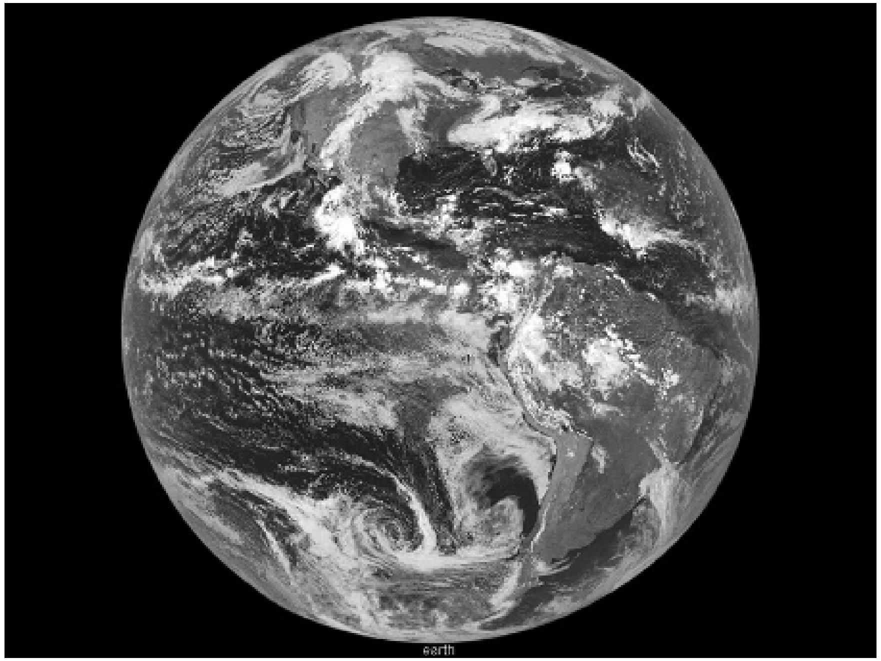
Energy Problem

Humanity's 10 Problem 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 9-10 Billion People

Nobel laureate Richard Smalley
Houston in 2003

Why Solar Cells ?

If installed 5kWp solar array for a typical home, over a single year, **it would prevent:**

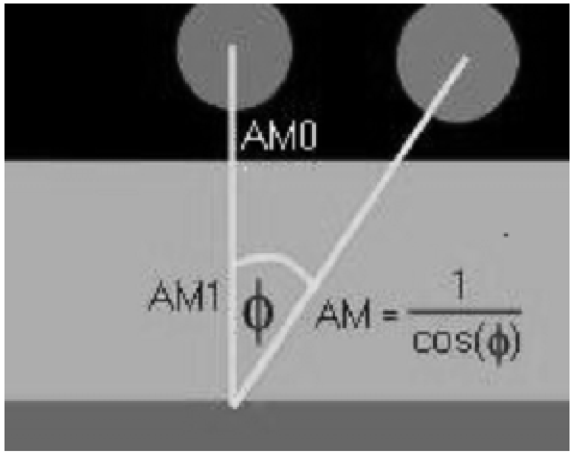
- 20000 lit of water
- 3.3 tones of coal from being burned
- 300 kg of ash from being disposed of landfills
- 30 kg of SO_2 and 25 kg of NO_x from causing acid rain
- 8.5 tones of CO_2 from enhancing the greenhouse effect

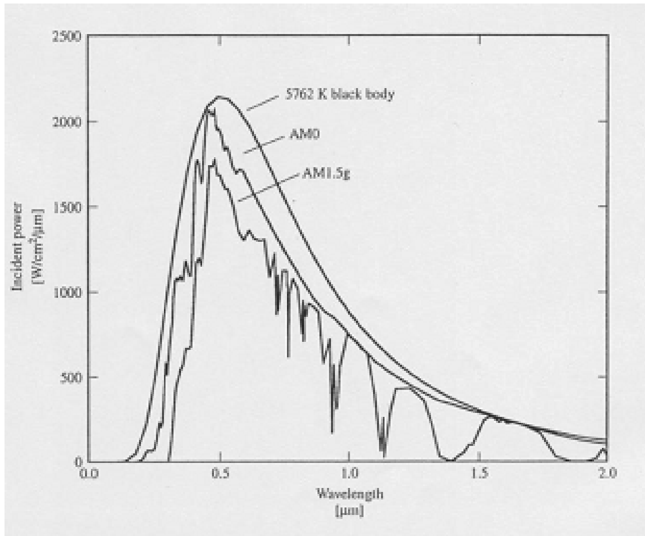
태양전지의 역사

연 대	특 징
1839 년	E. Becqurel, Photovoltaic (PV) effect 발견
1883 년	C. Fritts, 최초의 Se 태양전지 제작
1930 년	L. Grohndahl, Cu_2O/Cu 태양전지 연구
1941 년	R. Ohl, Si 태양전지 연구
1950 년대	반도체 기술 발전
1954 년	Bell Lab., 결정질 Si 태양전지 (효율 4%) 개발성공
1958 년	미국 우주선(Vanguard I) 보조전원 사용 (5 mW), 태양광 산업 태동
1970 년대	석유파동으로 지상용 전원으로 활용모색
1974 년	일본, 션샤인 계획 시작
1980 년대	태양전지 개발 본격화, 신재료 개발 (CdTe, $CuInSe_2$, TiO_2 등)
1991 년	M. Grätzel, 고효율 저가 광감응 염료 태양전지 발표 (Nature)
1999 년	환경친화적 발전기술로 부각, 전세계 연간 생산량 200MWp
2001 년	De Pauli, 고분자 전해질 염료감응 태양전지 최초 발표 (Adv. Mater.)

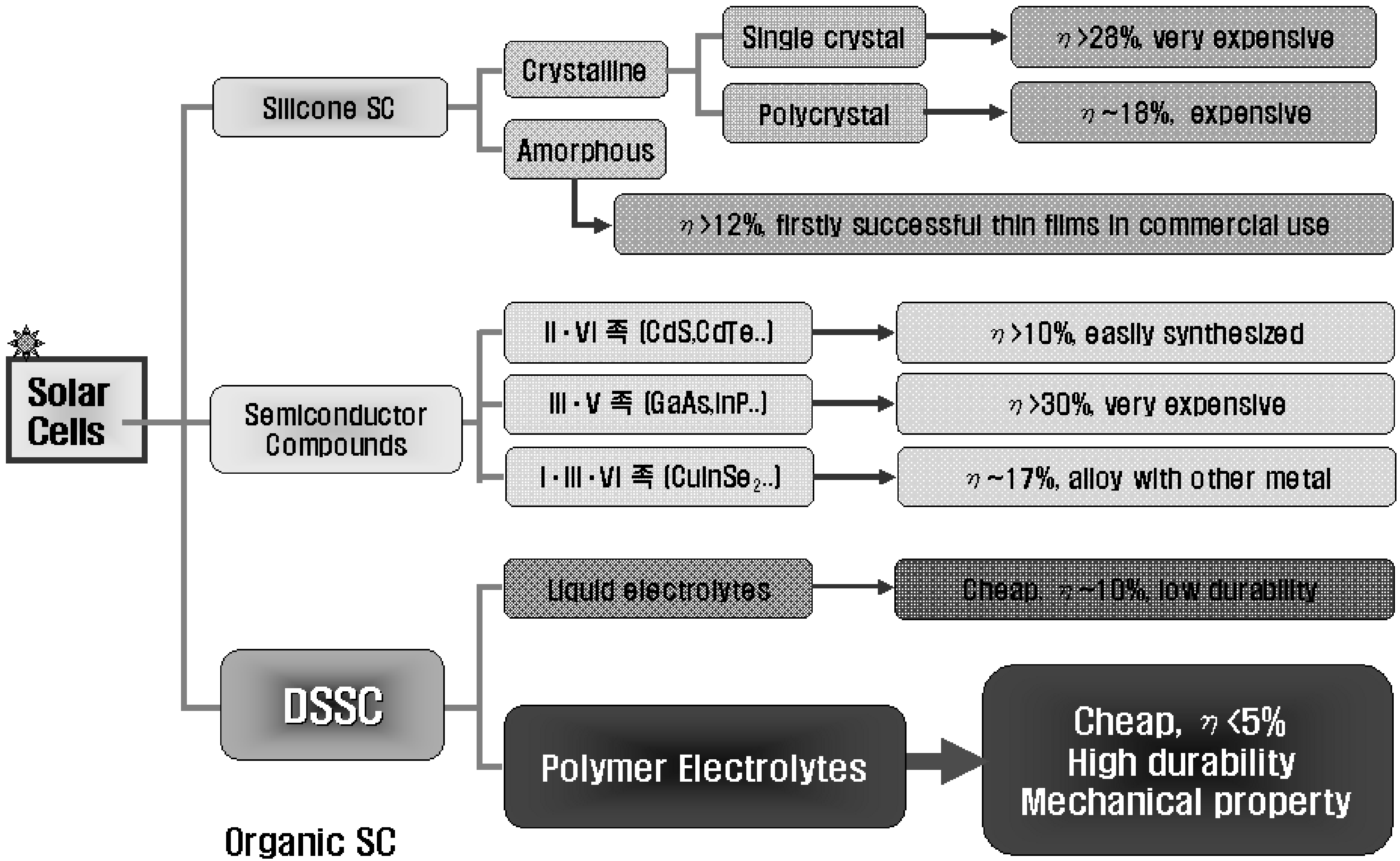
Terminology

- Photovoltaic : light + Alessandro Volta = light electricity
- Air Mass (AM)
  - degree of light decrease by absorption, reflection, refraction
  - AM0: outside atmosphere ~1367 W/m^2 (136.7 mW/cm^2)
  - AM α = 1/cosϕ ; angle from the horizon
  - AM1 : at ϕ = 48.2^o ~ one sun (1000 W/m^2)





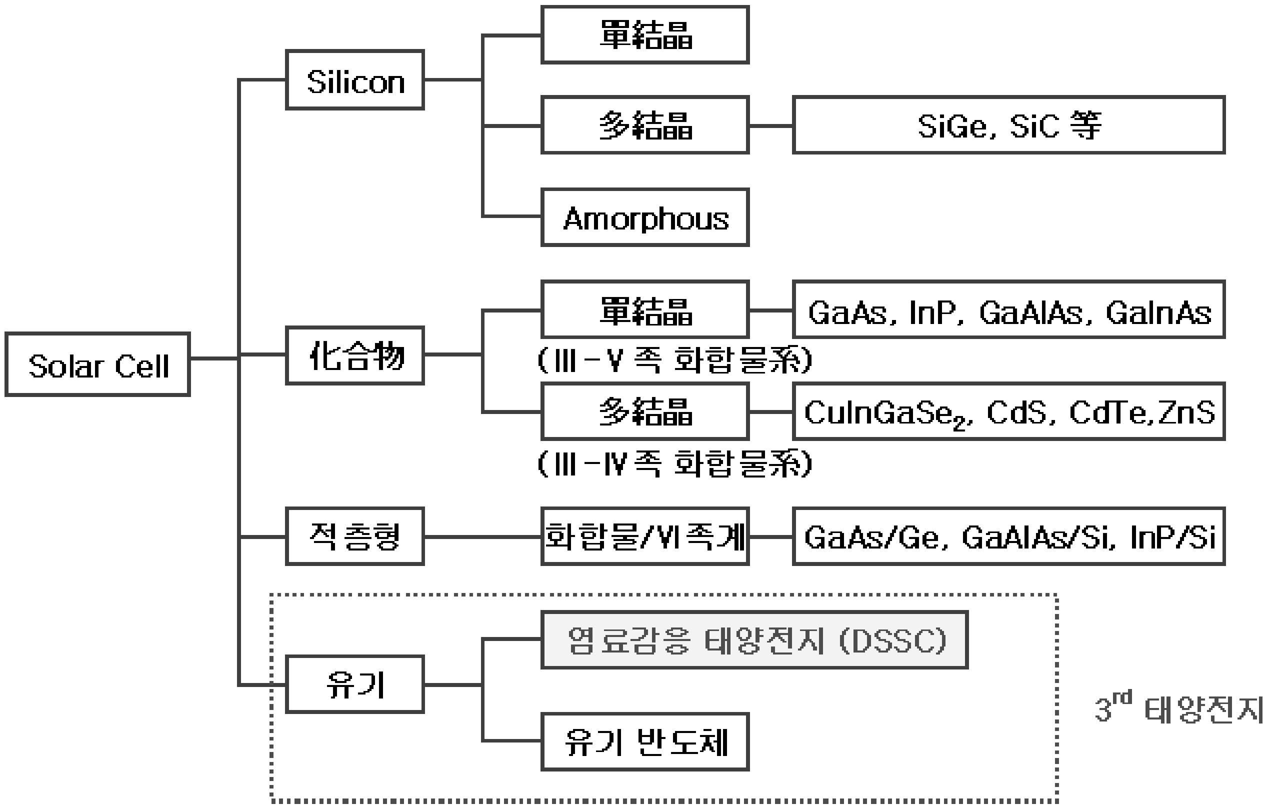
Types of Solar Cells



Generation of Solar Cells

Photovoltaics: from physics to nature

- 1st Generation: Silicon crystalline
- 2nd : Silicon amorphous, thin films
- 3rd : Nanotechnology & Biomimetics
- 4th : Biological



태양전지 비교

반도체 태양전지

장 점

- 고효율 (30% 이상) 태양전지 제조 가능

단 점

- 고효율 태양전지 제조 시 원료비용 및 제조비용 부담이 매우 큼
- 고순도를 요하는 공정이므로 제조공정이 복잡하고 어려움
- 환경에 유해한 물질 발생

광감응 염료 태양전지

장 점

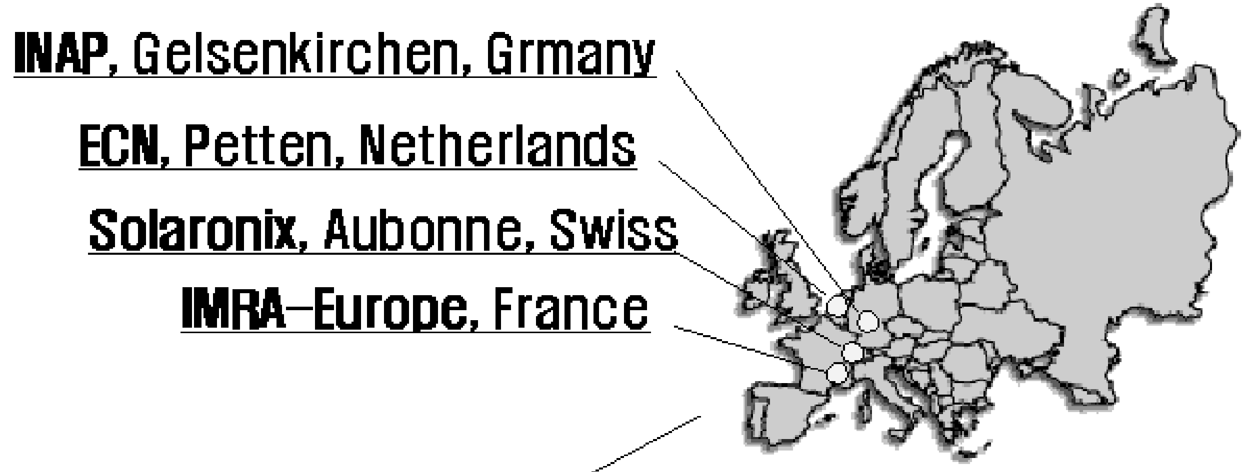
- 기존 비정질 실리콘 태양전지에 버금가는 에너지변환 효율 (습식 태양전지)
- 제조단가는 실리콘 태양전지의 5분의 1 수준
- 환경친화적 제조공정

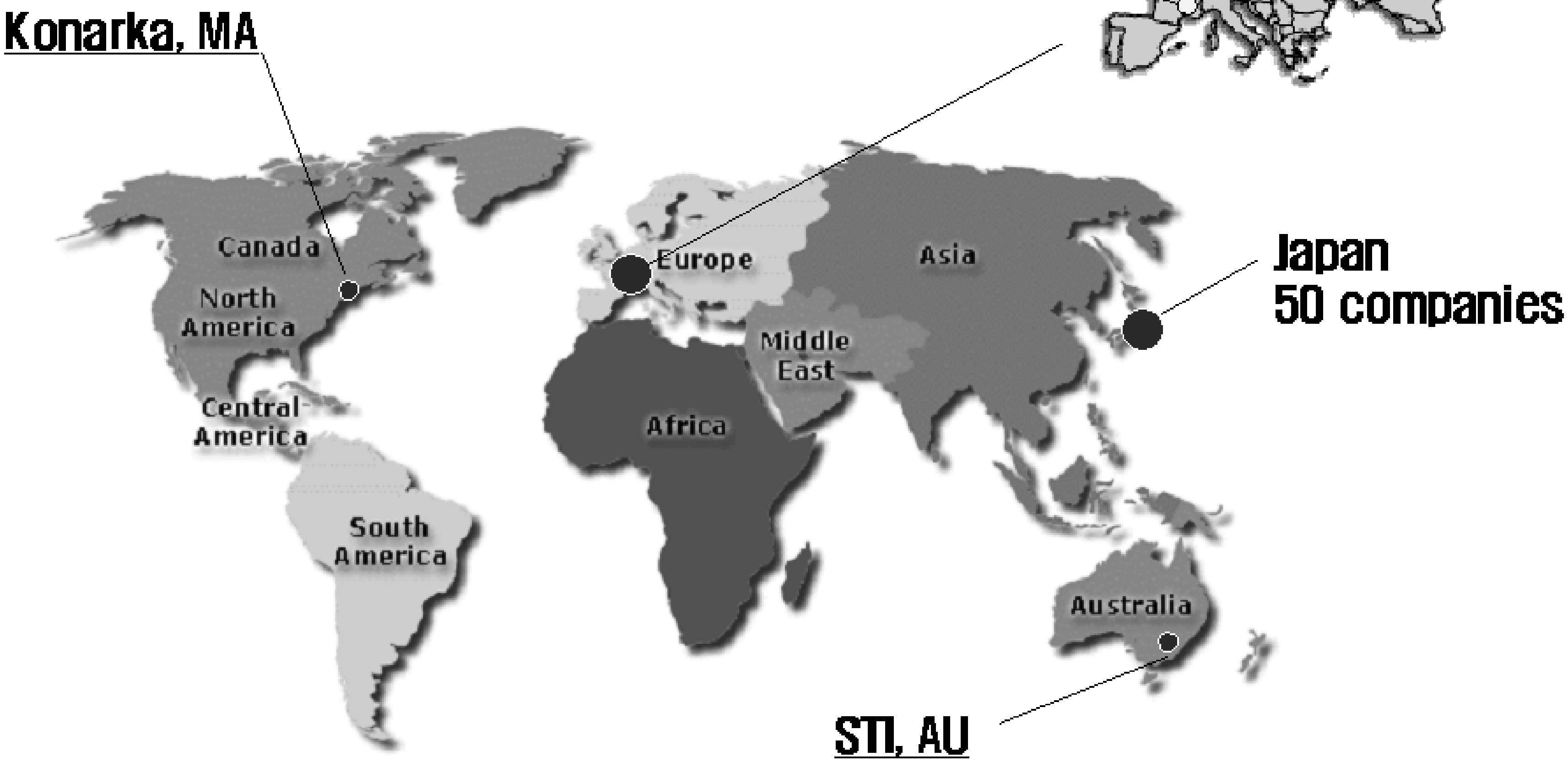
단 점

- 습식 태양전지의 경우, 용매의 휘발 및 누출에 따른 내구성 저하 문제

Trends in Industry

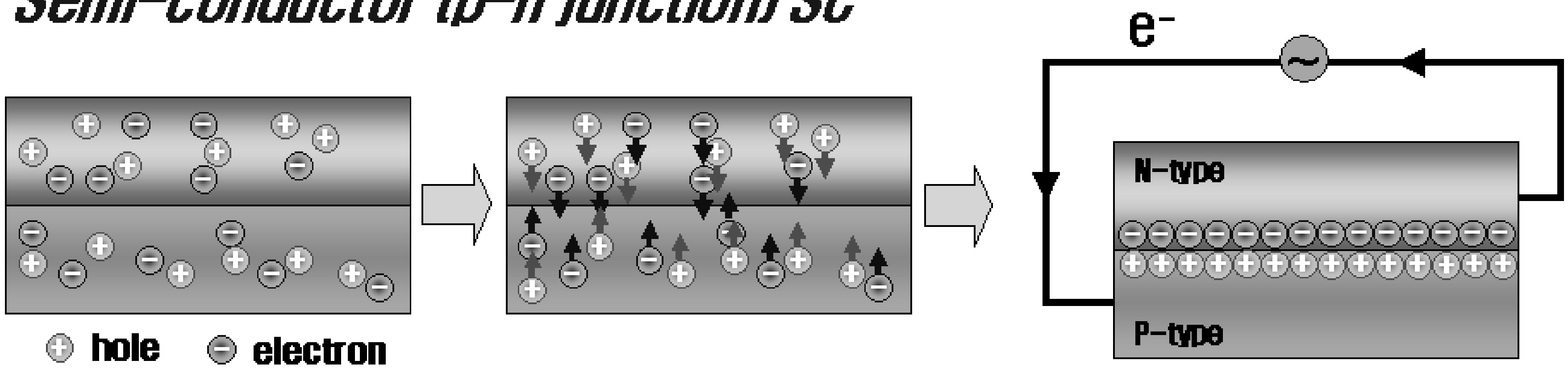
DSSC Manufacturers

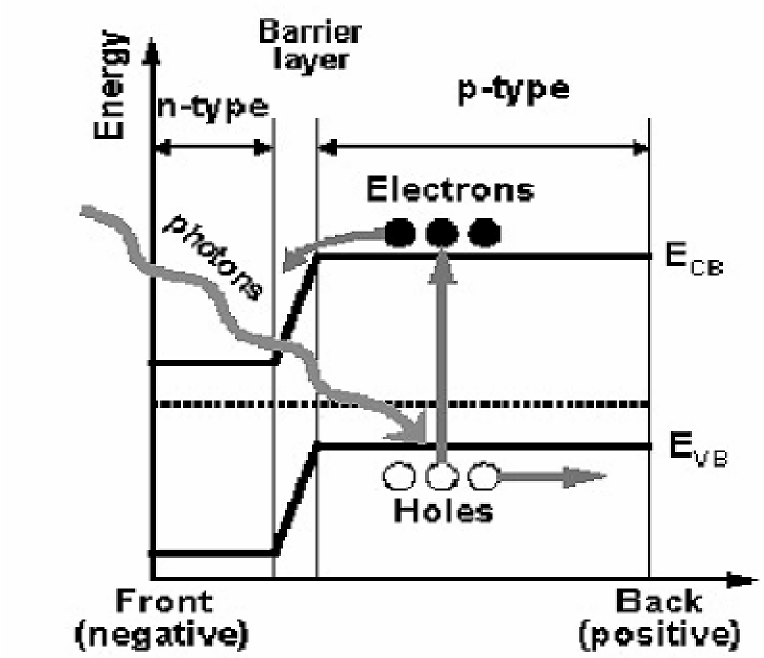




Principles of Inorganic Solar Cells

Semi-conductor (p-n junction) SC





N type: e⁻ transfer, e⁻ acceptor

P type: hole transfer, e⁻ donor

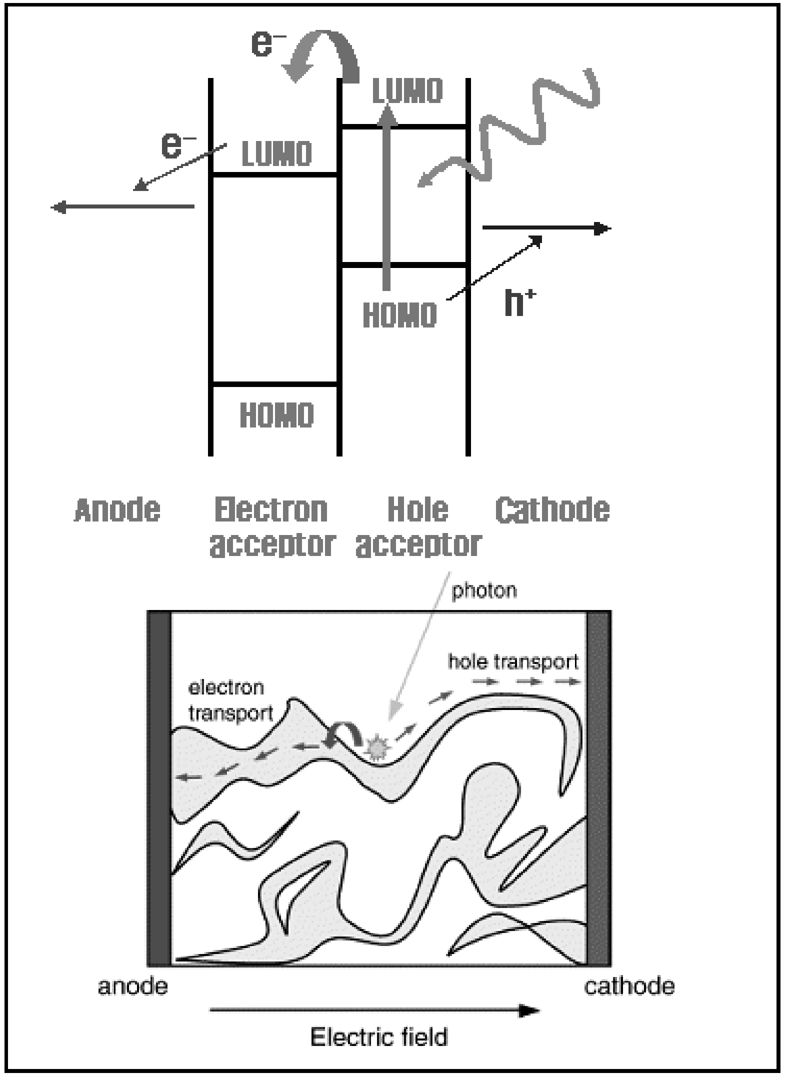
Band gap $E = E_{CB} - E_{VB}$

Photon with high $E > E_{BG}$

CB: conduction band, 전도띠

VB: valence band, 가전도띠

Organic Solar Cells



- Organic molecules
  - D-A heterojunction
  - dispersed heterojunction

Acceptor	Donor
Fullerene	Conducting P
Conducting P	Conducting P
Nano-inorganics	Conducting P

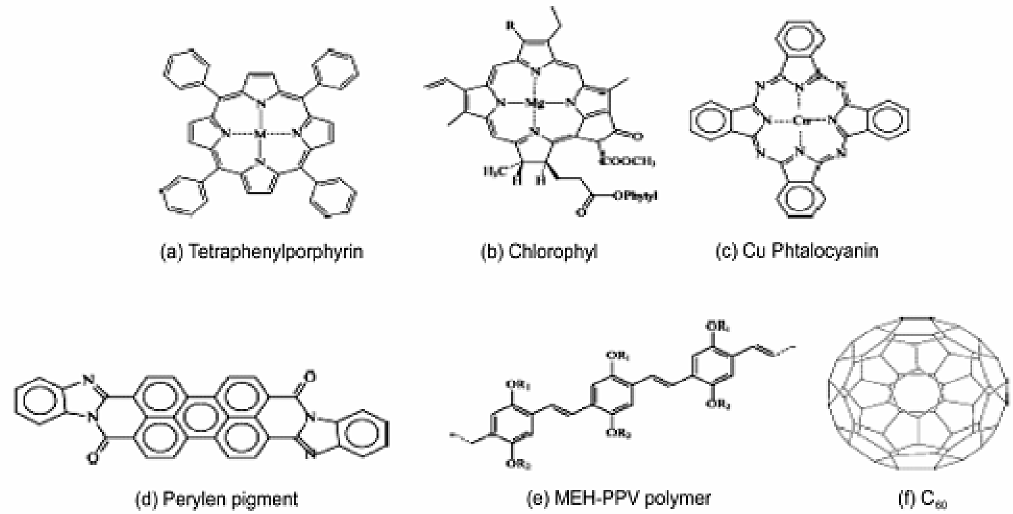
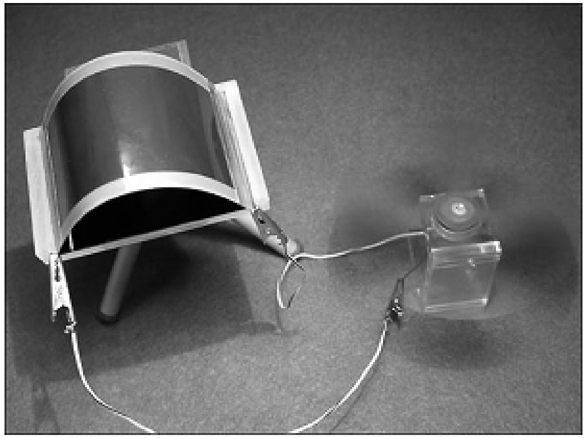
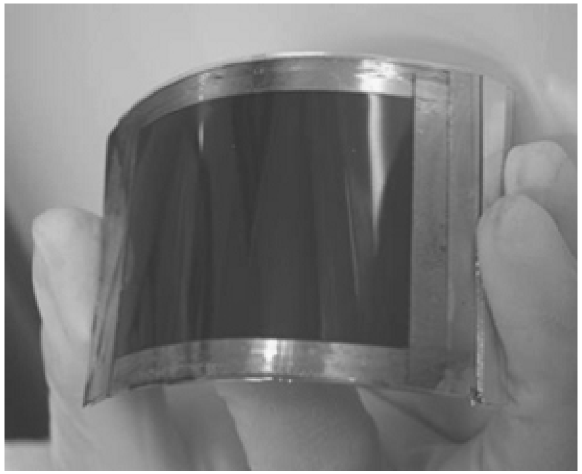


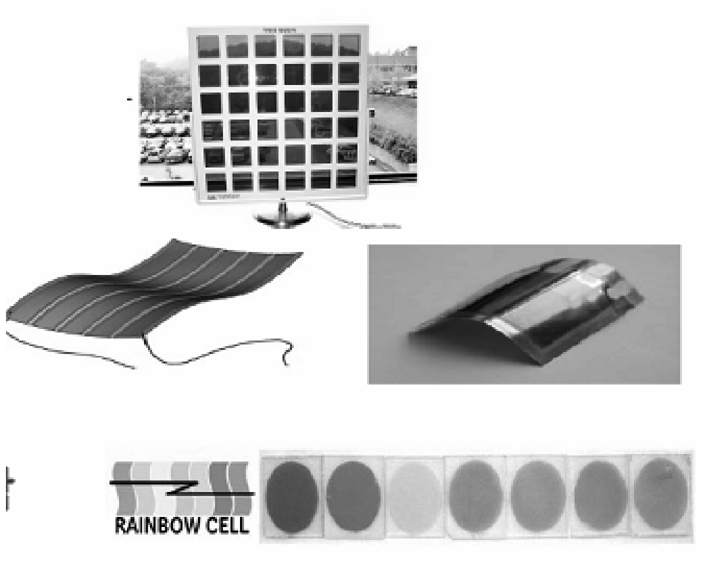
Fig. 13. Materials for organic solar cells: (a)-(c): donors, (d)-(e): acceptors.

Organic Solar Cells



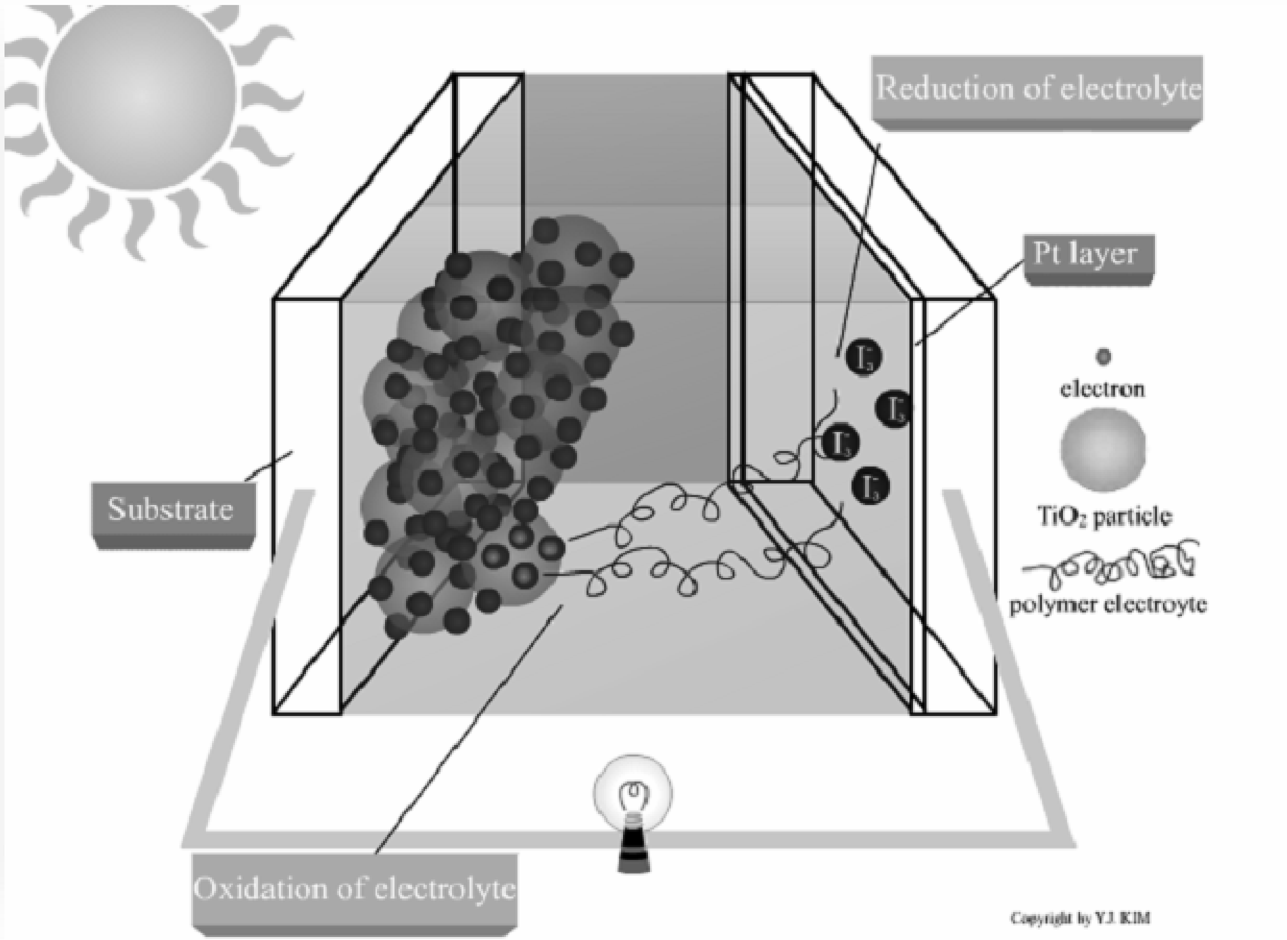
- Organic Solar Cells
  - Cheap, efficient
  - Improved stability
  - Transparent, flexible, colorful





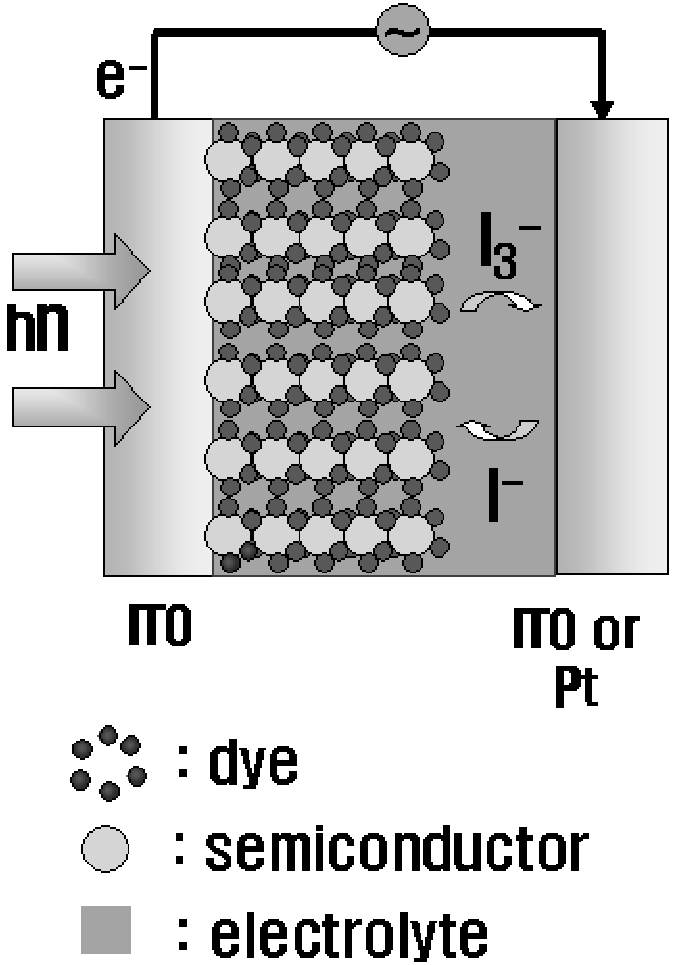
Principles of Solar Cells

※ *Dye-Sensitized Solar Cells (DSSC)*

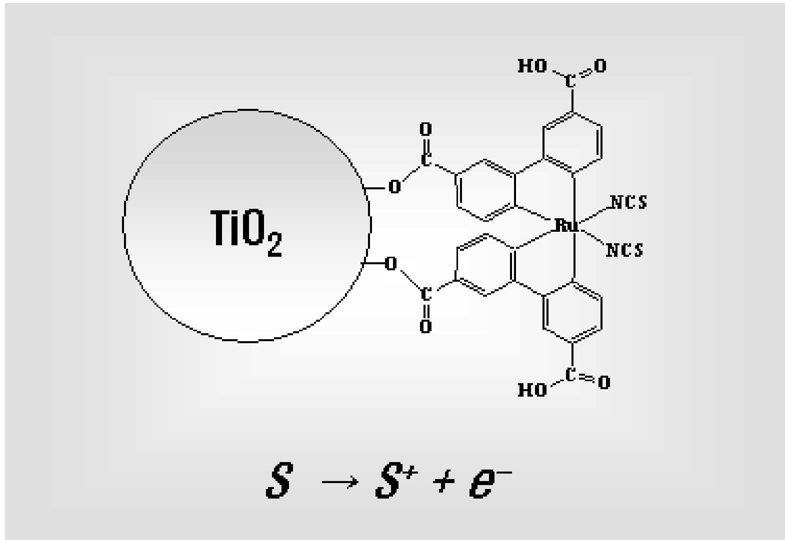


Principles of Solar Cells

※ *Dye-sensitized solar cells*



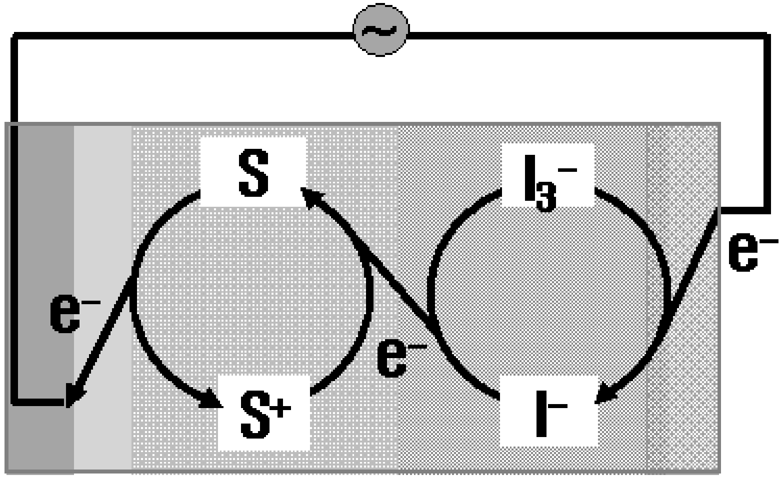
Ru Dye (sensitizer)/TiO_2



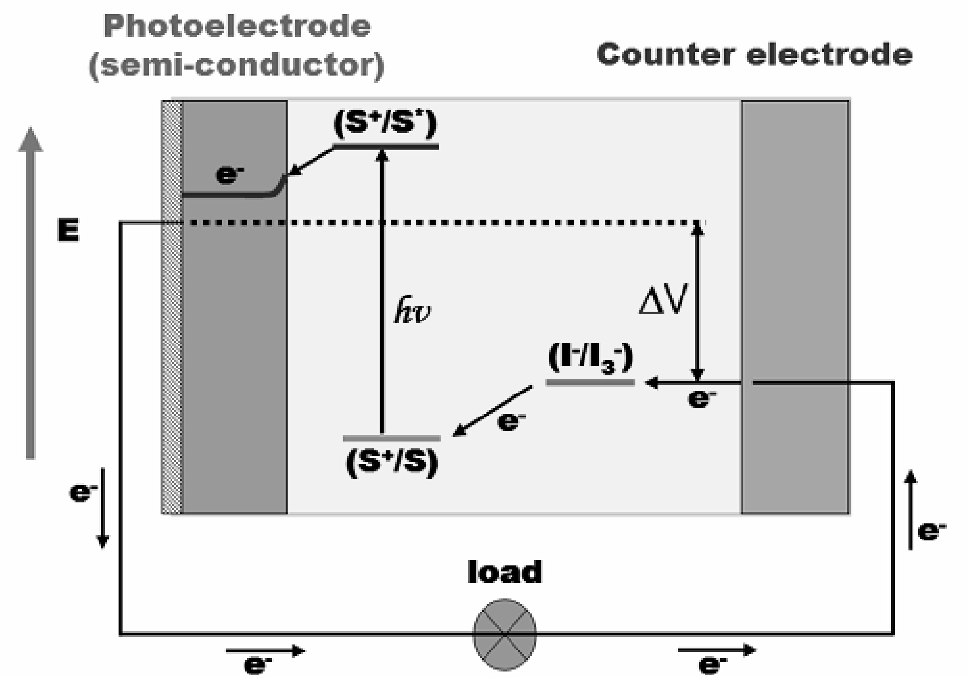
Redox couple : $3I^- \leftrightarrow I_3^- + 2e^-$

Principles of Solar Cells

Dye-sensitized solar cells (DSSC)

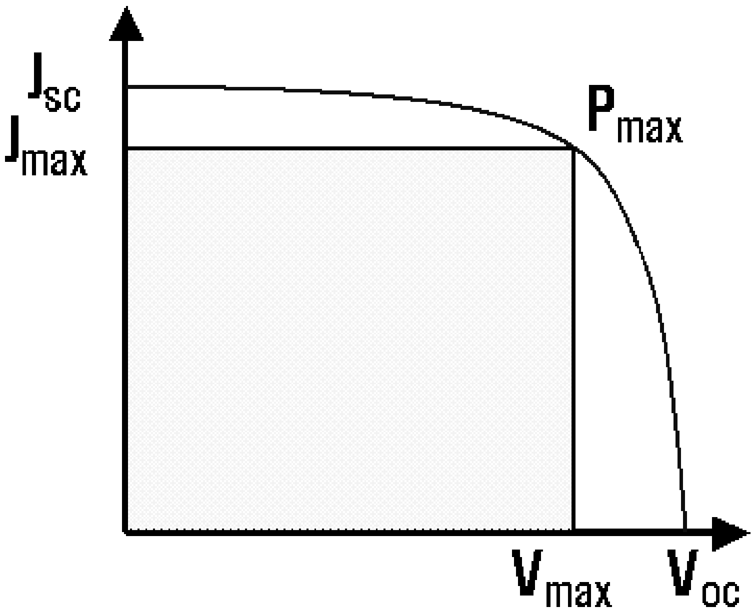


$$S \rightarrow S^*$$
$$S^* \rightarrow e^-(TiO_2)_{cb} + S^+$$
$$2S^+ + 3I^- \rightarrow 2S + I_3^-$$
$$I_3^- + 2e^- \rightarrow 3I^-$$



Performance of Solar Cells

Typical J-V curve of solar cell



$$FF = \frac{V_{\max} \cdot J_{\max}}{V_{oc} \cdot J_{sc}}$$

$$\eta(\%) = \frac{V_{\max} \cdot J_{\max}}{P_{in}} \times 100$$
$$= \frac{V_{oc} \cdot J_{sc} \cdot FF}{P_{in}} \times 100$$

Solar cell performance

- V_{OC} : Open-Circuit Voltage, J_{SC} : Short-Circuit Current
- FF: Fill Factor, η : Overall Conversion Efficiency

Characteristics of DSSC

- promising candidates for renewable clean energy source

Low Costs : 1/3 ~1/5 of conventional Si S/C

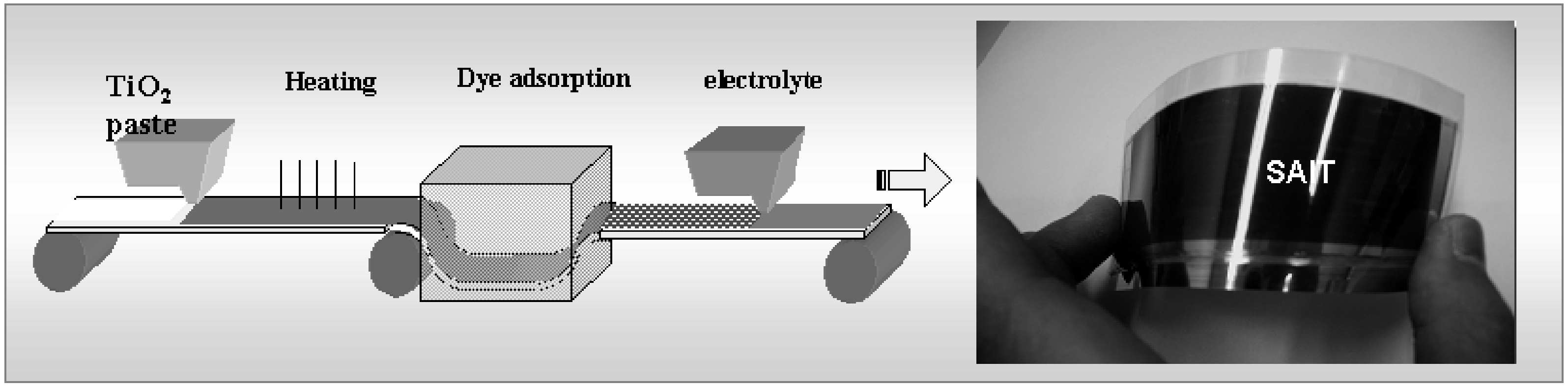
Green Technology: non-toxic mater.

Transparent: Power window, smart window

Coloration: Rainbow cell

Flexibility: Flexible Battery & Device

TOYOTA-AISIN精機

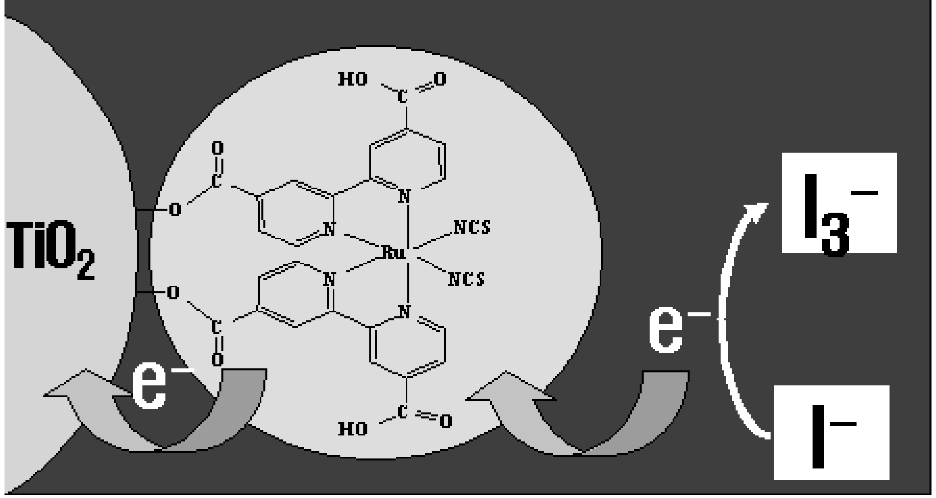


Roles of Electrolytes

Electrolytes:

- I^- and I_3^- conductor
- interfacial contactor for dye
- electron barrier or hole conductor
- electrochemical reaction media
- mechanical separator

Contact of electrolyte with dyes:

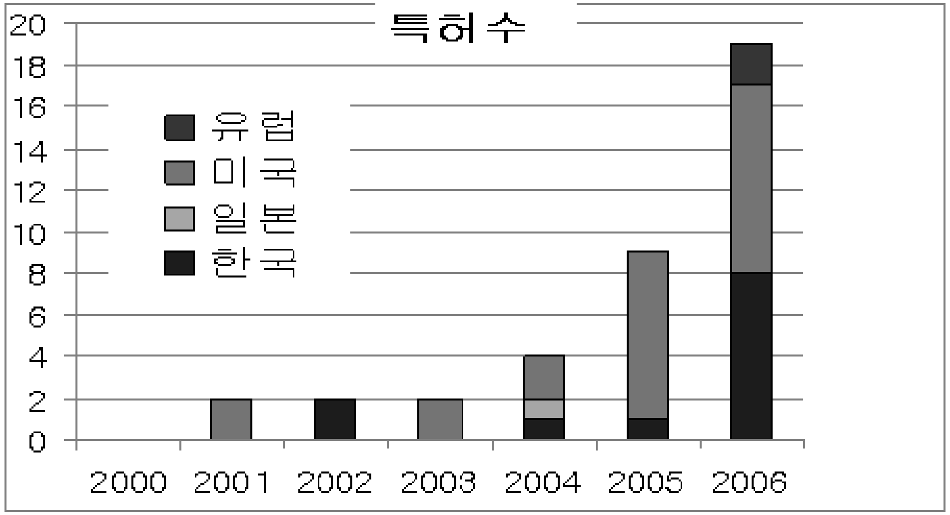


Why Polymer Electrolyte DSSC ?

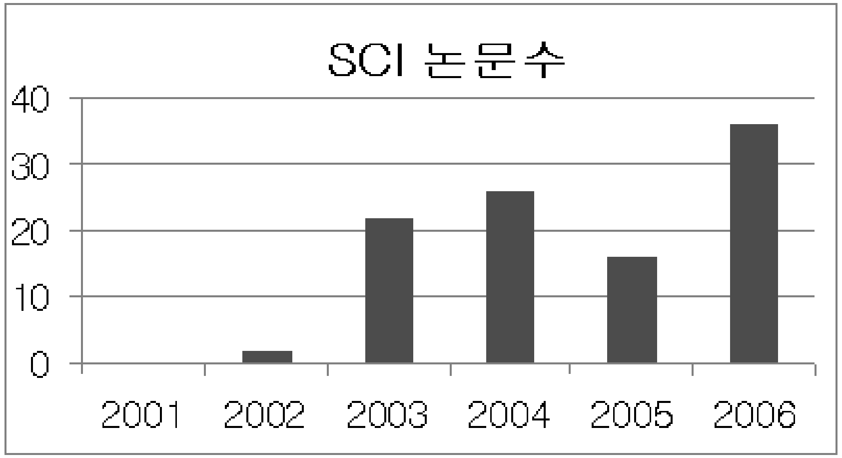
- Cheap (1/5 of Silicone solar cell)
  Environmentally friend.
- Thin, Flexible, light
- Higher durability using solid or gel type solar cell
- World-wide great attention very recently

Research Trends in PE-SC

- **WIPS Patent**



- **Web of Science SCI Paper**




Break ???

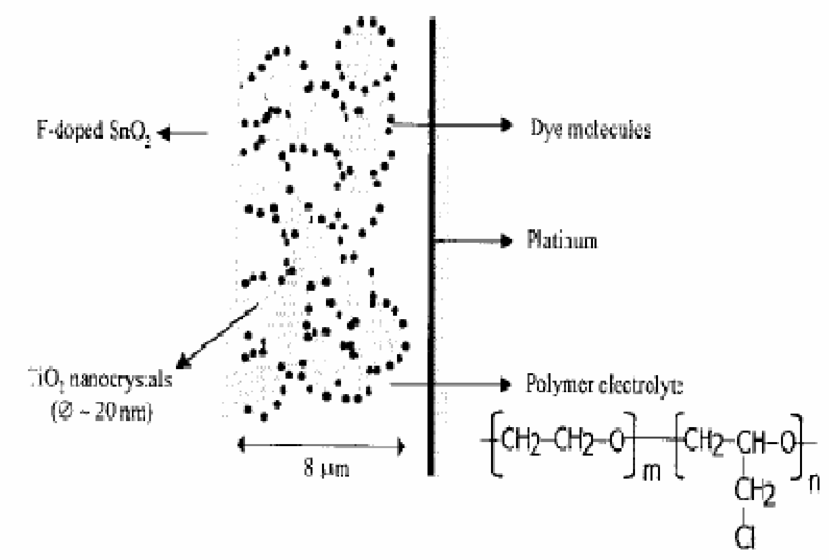
Polymer Electrolytes Review – 1

- Title: Dye-sensitized nanocrystalline solar cells employing a polymer electrolyte
- Authors: De Paoli et al. [Brazil]
- *Adv. Mater.* 2001, 13, 826.

HIGHLIGHTS

☞ ***Epychlomer(1.3M)/NaI/I_2***

- *High efficiency*
  : 2.6 % at 10mW/cm^2
- *Successful penetration*
  – due to nature and viscosity of polymer electrolytes



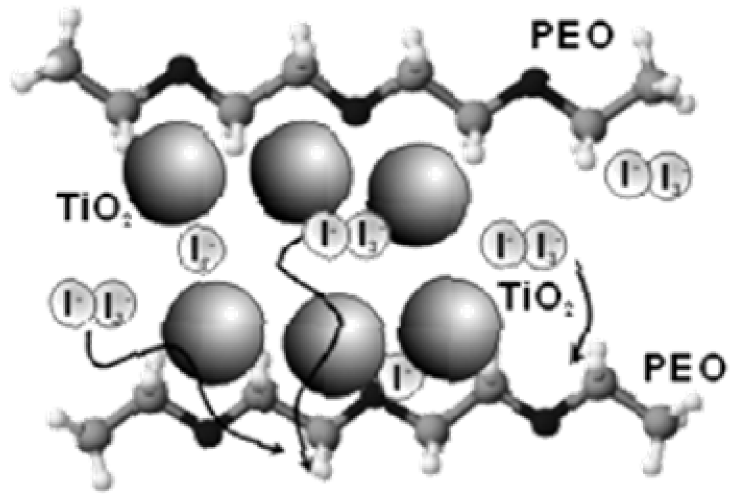
Polymer Electrolytes Review – 2

- Title: Binary polyethylene oxide/titania solid-state redox electrolyte for highly efficient nanocrystalline TiO_2 photoelectrochemical cells
- Authors: Stergiopoulos, T. et al (Greece)
- *Nano Letter*, 2002, 2, 1259.

HIGHLIGHTS

☞ ***PEO(2M)/TiO_2/LiI/I_2***

- *Reduced crystallinity*
- *Enhanced the mobility of I^-/I_3^-*
- *outstanding efficiency (4.2%)*



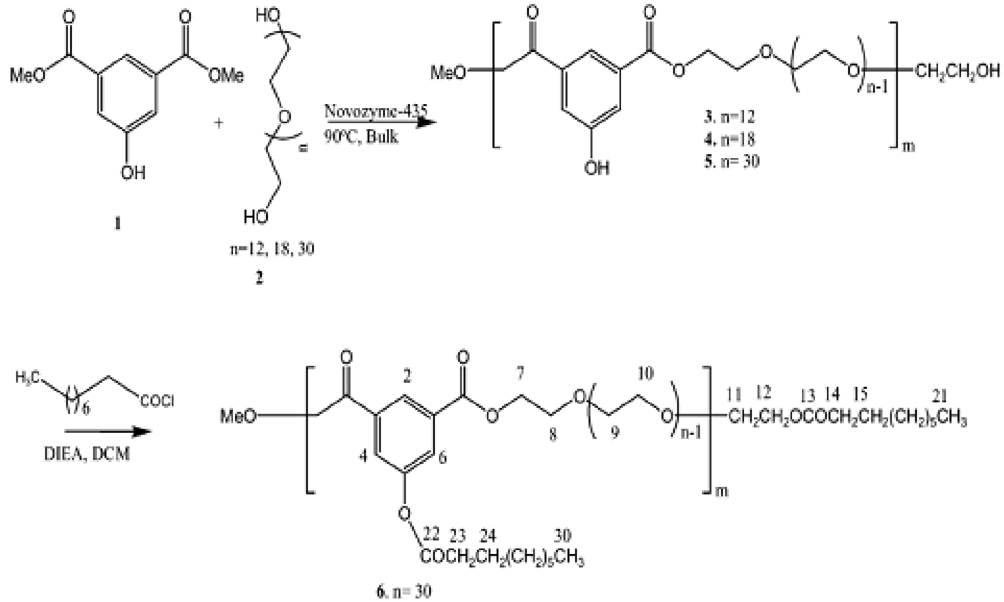
Polymer Electrolytes Review - 3

- Title: Flexible, Dye-Sensitized Nanocrystalline Solar Cells Employing Biocatalytically Synthesized Polymeric Electrolytes
- Author: Rajesh Kumar et al. (University of Massachusetts)
- *Chem. Mater.* 2004, 16, 4841.

HIGHLIGHTS

☞ PEGylated polymers

- *Biocatalytic approach*
  -Novozyme catalyzed reaction
- *outstanding efficiency (4.6%)*



Other Polymer Electrolytes

[1]. Y. Ren et al. "Application of PEO based gel network polymer electrolytes in dye-sensitized photoelectrochemical cells", *Solar Energy Materials Solar Cells*, 2002, *71*, *253.*

[2] O. A. Ileperuma, "Dye-sensitised photoelectrochemical solar cells with polyacrylonitrile based solid polymer electrolytes", *Electrochimica Acta*, 2002, *47, 2801.*

[3] J. Kang, "Polymer electrolytes from PEO and novel quaternary ammonium iodides for dye-sensitized solar cells, *Electrochimica Acta*, 2003, *48, 2487.*

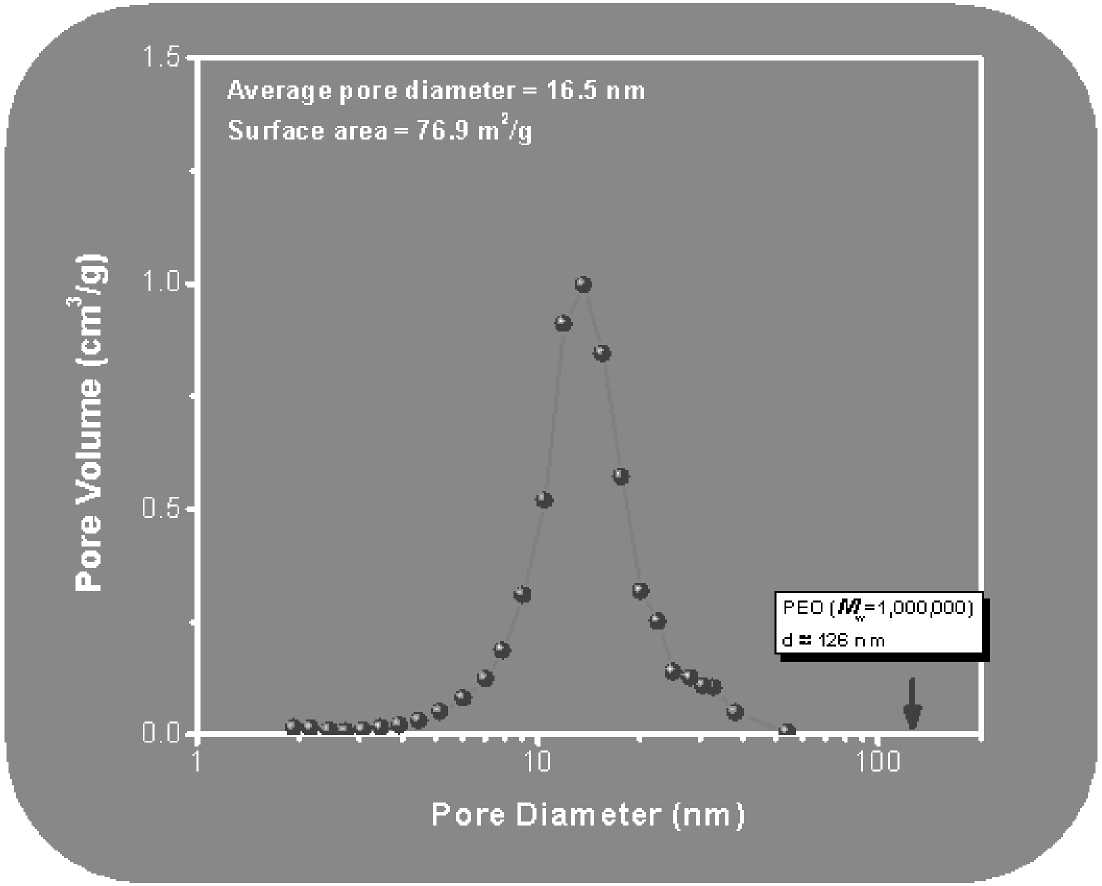
[4] G. Wang, "Gel polymer electrolytes based on polyacrylonitrile and a novel quaternary ammonium salt for dye-sensitized solar cells", *Materials Research Bulletin*, 2004, *39, 2113.*

[5] W. Li, "A novel polymer quaternary ammonium iodide and application in quasi-solid-state dye-sensitized solar cells", *J. Photochem. Photobio. A: Chem. 2005, 170, 1.*

[6] J. Wu, "Gel polymer electrolyte based on poly(acrylonitrile-co-styrene) and a novel organic iodide salt for quasi-solid state dye-sensitized solar cell", *Electrochimica Acta*, 2006, *51, 4243.*

Why Low Efficiency ?

Pore Size Distribution – BET



FE-SEM image of TiO_2 electrode

Why Low Efficiency ?

$$R_g = c \cdot M_w^{\,0.5\pm0.1} \quad \text{(nm)}$$

- Poly(ethylene oxide) (PEO)

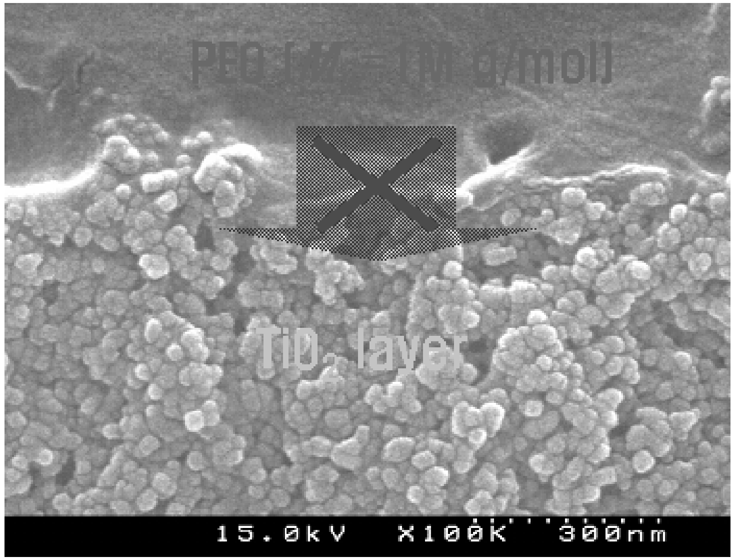
  c=0.063 (in diluted solution)

  c=0.042 (in molten state)

- ***Example: PEO (Mw=1,000,000)***

  R_g= 63 nm (in diluted solution)

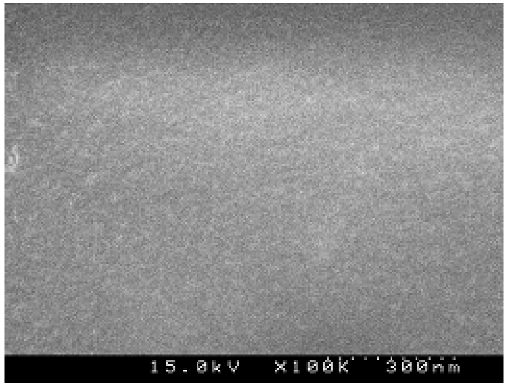
  R_g= 42 nm (in molten state)



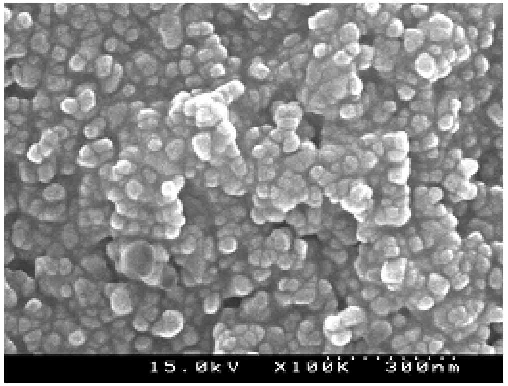
> TiO_2 pore size (~16.5 nm)

- Poor penetration
- Low conductivity

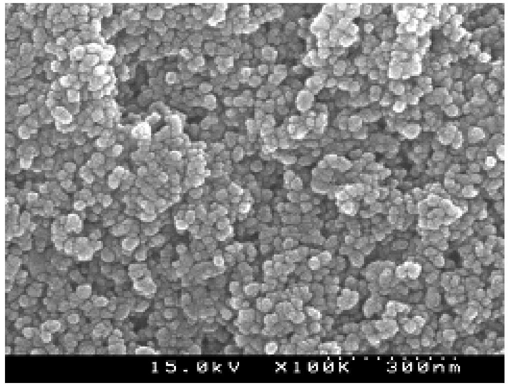
FE-SEM images – Size balance



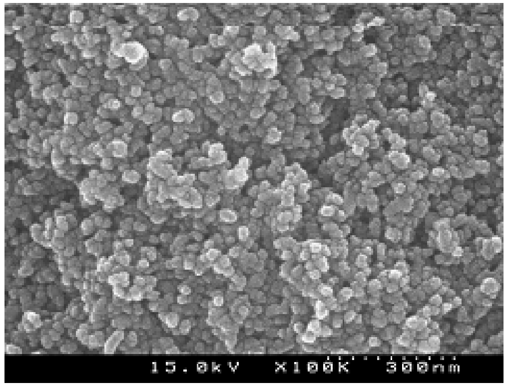
M_W=1K
(R_g=2.0 nm)



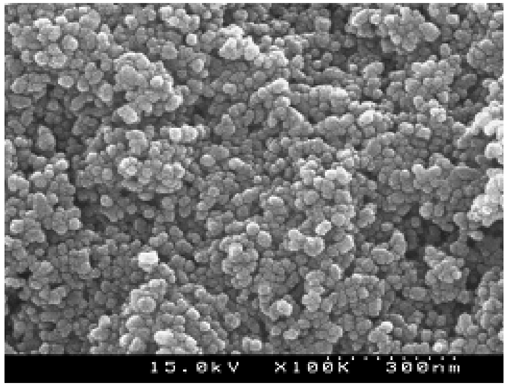
M_W=4.6K
(R_g=4.3 nm)



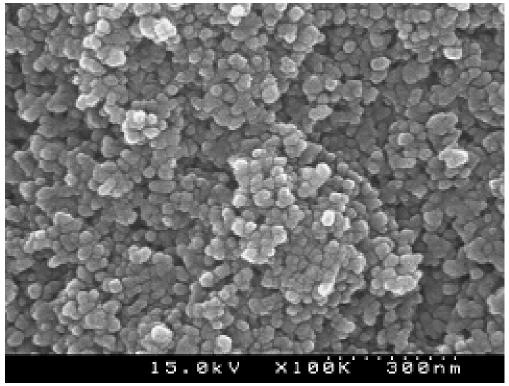
M_W=8K
(R_g=5.6 nm)



M_W=10K
(R_g=6.3 nm)



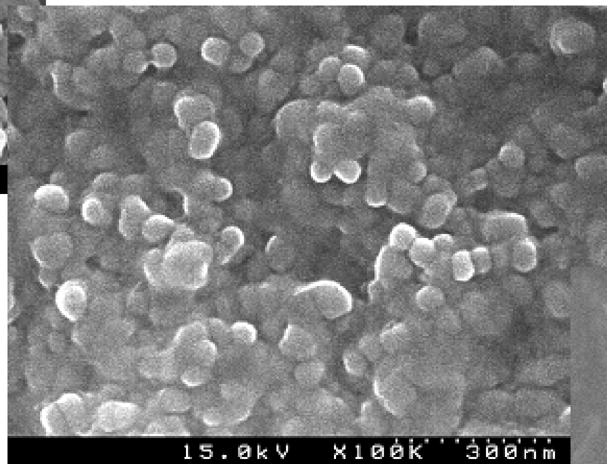
M_W=100K
(R_g=19.9 nm)



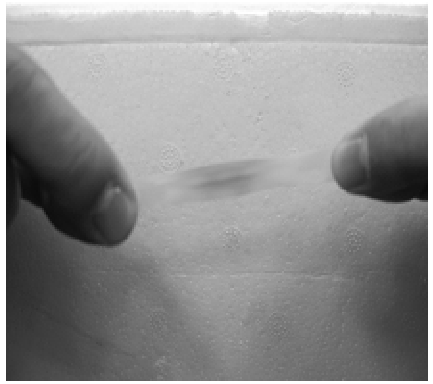
M_W=600K
(R_g=48.8 nm)

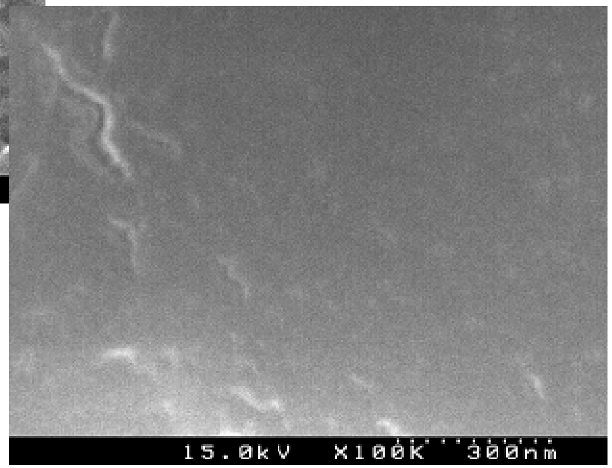
Size balance vs. Efficiency

η = 0.01 %



η = 1.25 %





η = 3.84 %

Low Mw PEs

- better penetration
- high conductivity
- poor mechanical property

Oligomer Approach

Prof. Kang at Hanyang Univ. /
Prof. Kim at Yonsei Univ.

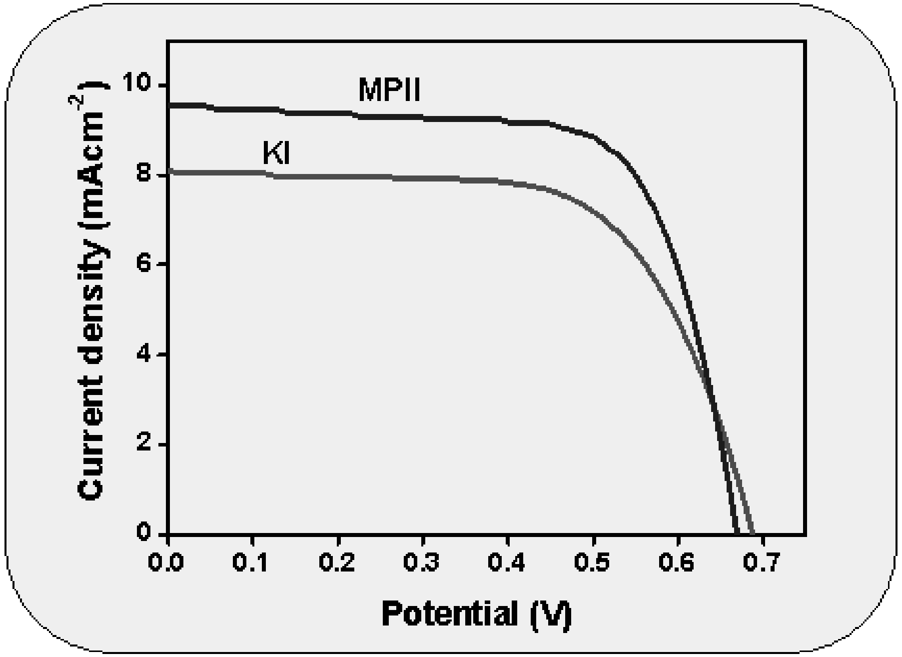
- ***Oligomer : Mw ~ 1000, liquid ($R_g < 3$ nm)***
- ***To enlarge the interfacial contact area between dyes and electrolyte***
- ***To improve the ionic conductivity***

during preparation (liquid oligomer) → after preparation (solid polymer)

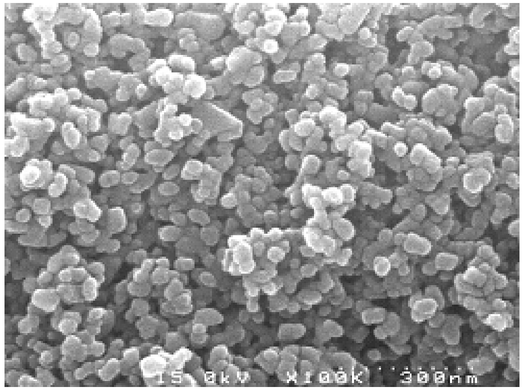
in situ solidification during solvent evaporation

HB Polymer Electrolytes

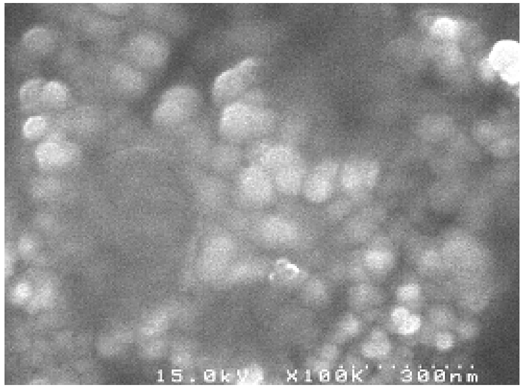
☞ PEO + Silica Nanoparticles



Efficiency 4.5%
Fill factor 70.0%
at 100 mW/cm^2



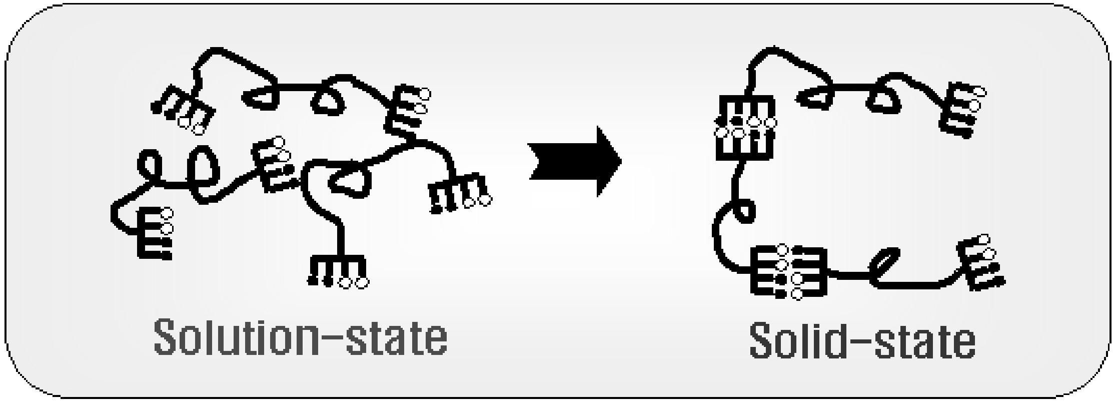
[a] Bare TiO_2 layers



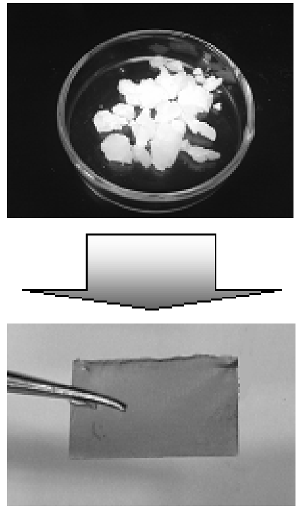
[b] TiO_2 with PEs

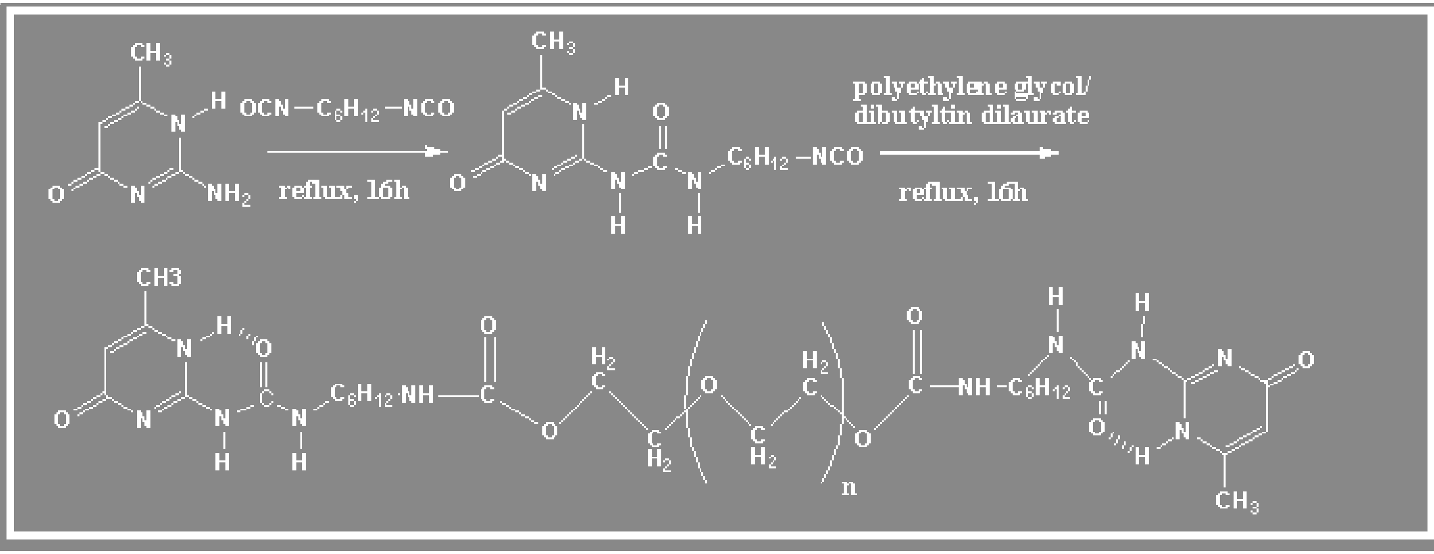
Quadruple HB Polymer (QHBP)

Design of Electrolytes



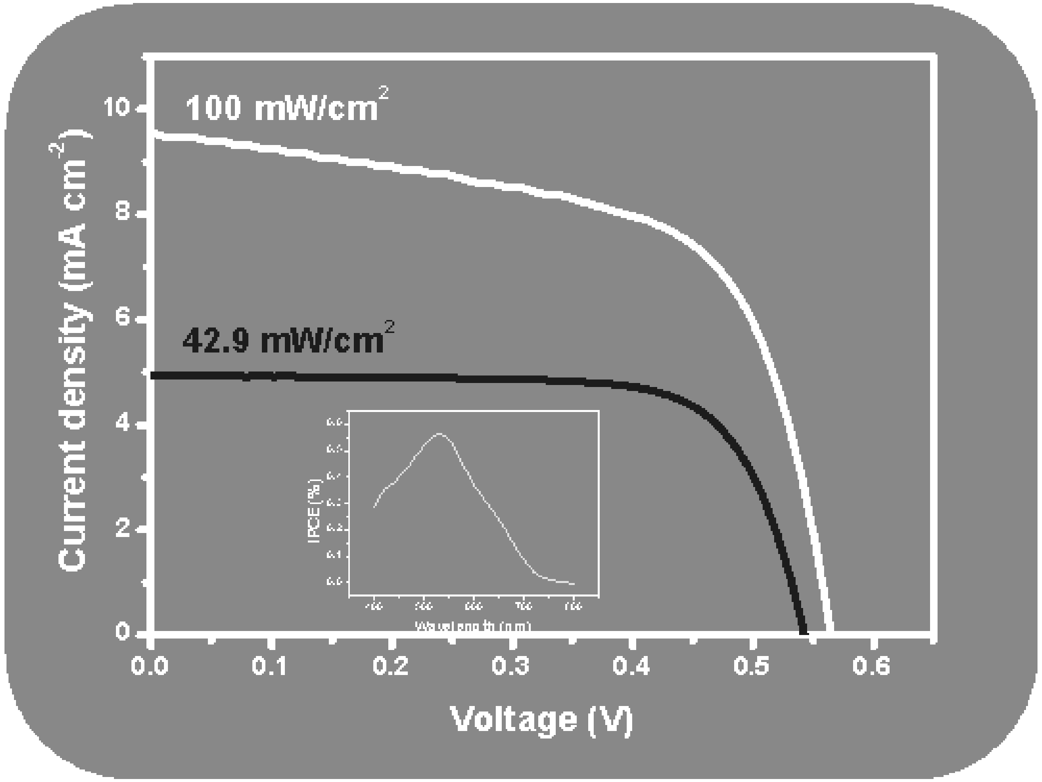
PEG: 1,000 g/mol





Cell Performance

Energy Conversion Efficiency



V_{oc} : 0.57 V

J_{sc} : 9.53 mA/cm^2

FF : 62 %

η : <u>3.34 %</u> (4.6% at 42.9 mW/cm^2)

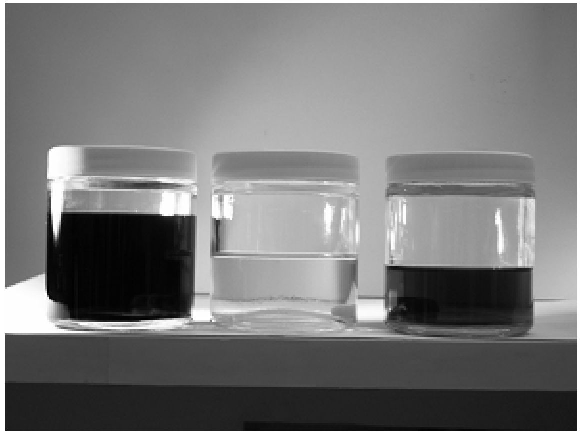
P_{in} : 100 mW/cm^2

J–*V* curves of DSSCs using QHBP/MPII electrolyte

Solid State DSSC

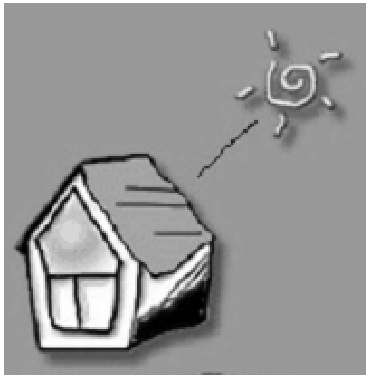
Power window

Large area (20x20 cm^2)



dyes

Results about Solar Cells



Solid organic solar cell

2.6 % at 0.1 sun and 1.6 % at 1 sun
by de Pauli group: *Adv. Mater.* 2001, 13, 826
Epychlomer/NaI/I_2

4.2 % at 0.65 sun
by Stergiopoulos group: *Nano Letters* 2002, 2, 1259
PEO/TiO_2/LiI/I_2

8.1 % at 0.1 sun
4.5 % at 1 sun

The Highest values !!!!
Prof. Kang at Hanyang Univ. /
Prof. Kim at Yonsei Univ.

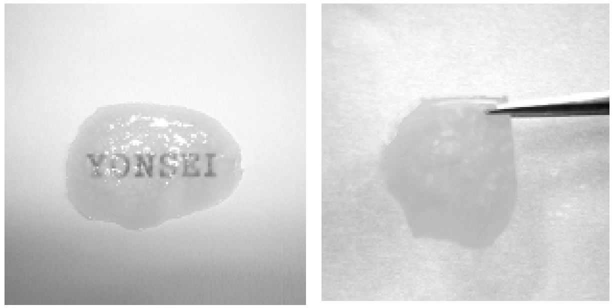
Adv. Mater, Chem. Commun. J. Phys. Chem.
(2004, 2005, 2006)
Press & Broadcasting (2004)

One-step Synthesis

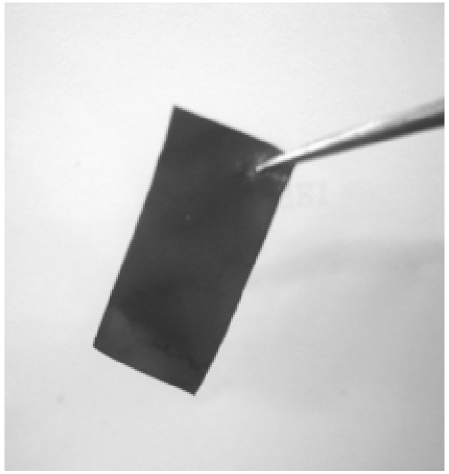
Prof. Kim at Yonsei Univ.

Pristine Polymer

QHBP



QHBP/KI



QHBP/KI/I_2

Recent Research Trends

1. Nanocrystalline Oxides
Surface Modification
Morphology Modification (nanorod...)
Bilayer Structure
TiO_2, SnO_2, ZnO, Nb_2O_5......

2. Electrolytes
High Boiling Point & Low Viscous Sovent
Polymer Electrolyte
Solid State (including p-type conductors)
Room Temp. Molten Salt

3. Dye Molecules
Modification of Ruthenium Complexes
Organic Dye, Inorganic Dye
Natural Products

4. Basic Researches
Electron Transport Mechanism
IMPS, IMVS, EIS, Random Walk etc.

Higher Efficiency !!

Current Issues

1. Understanding electron dynamics in DSSCs
2. Electrolyte evaporation and degradation
   → Quasi or solid state DSSCs
3. New sensitizers (dye or quantum dot)
4. Recombination in the oxide layer
   → Preparation of the second oxide layer for passivation
5. Flexible DSSCs
6. Increasing efficiency and performance
7. Long-term performance