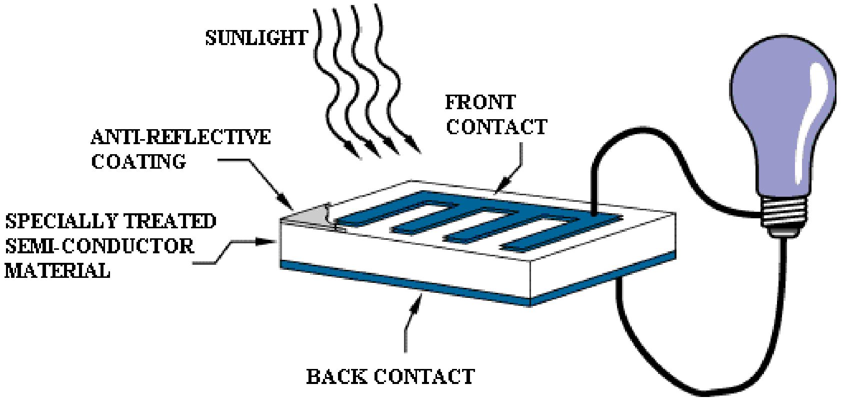
Chapter 3. Organic photovoltaics
(solar cell principle)

What is PV?

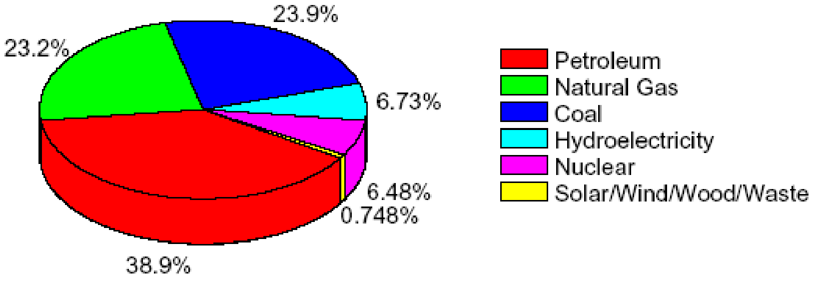
Light energy (photons) ➡ **Electrical energy**



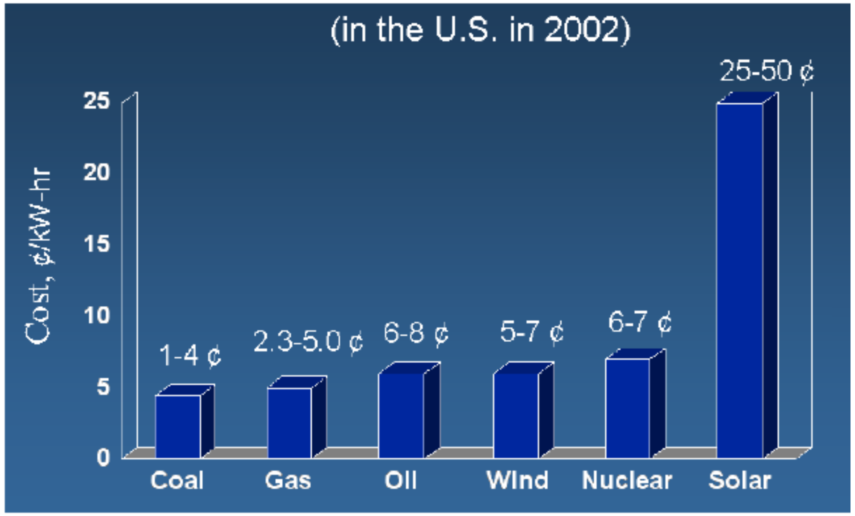
When sunlight is absorbed by some materials, the solar energy knocks electrons loose from their atoms, allowing the electrons to flow through the material to produce electricity. This process of converting light (photons) to electricity (voltage) is called the ***photovoltaic (PV) effect***.

Introduction – Solar cell (photovoltaic)

At earth's surface average solar energy is ~ 4 x 10^{24} J / year
Global energy consumption (2001) was ~ 4 x 10^{20} J / year (increasing ~ 2% annually)



Source: DOE (U.S. Department of Energy)



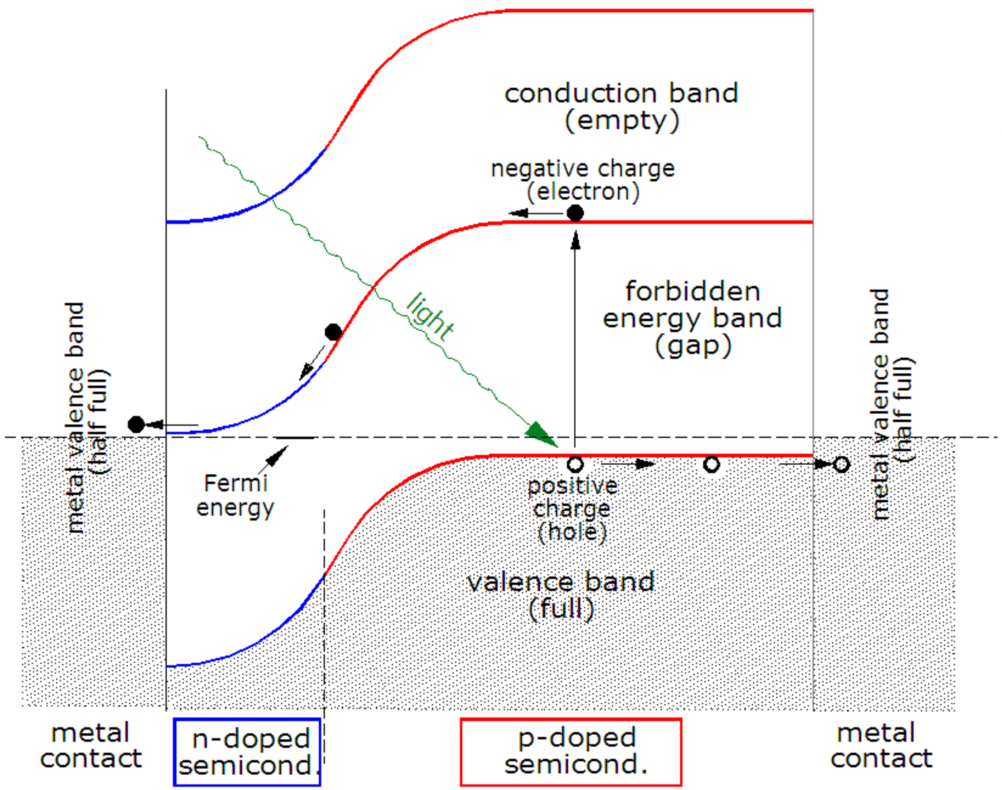
Source: N. Lewis (Caltech)

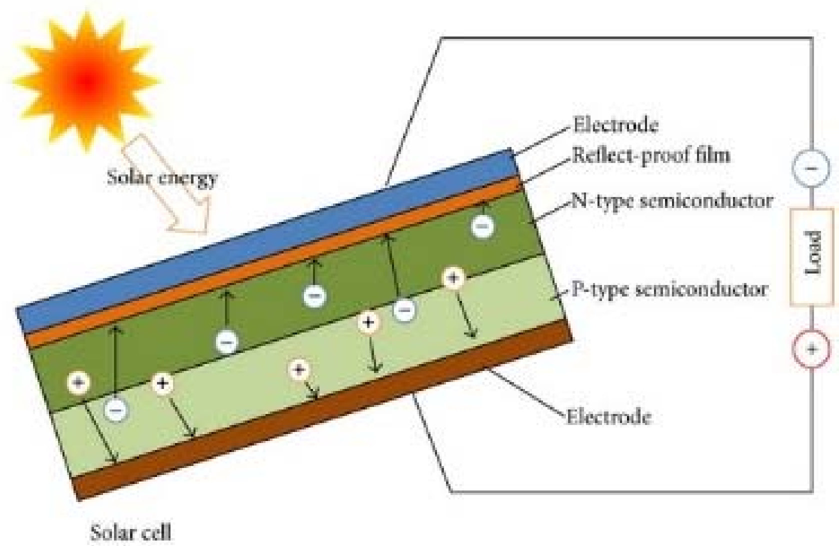
In US, average power requirement is 3.3 TW.
With 10% efficient cells we would need 1.7% of land area devoted to PV (~ area occupied by interstate highways)

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 an advanced materials and structures
  (dye sensitized solar cell, organic solar cell)
  ➔ cheap process , flexible substrate

PV effect

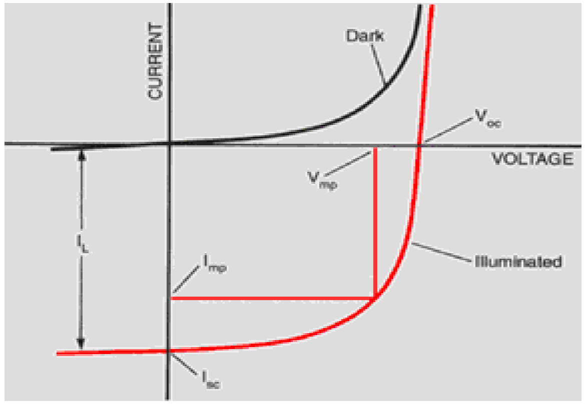




conventional semiconductor, light absorption generates an electric field that separates the photo-induced charges. *Ec* and *Ev* are the energies at the conduction and valence bands, respectively.

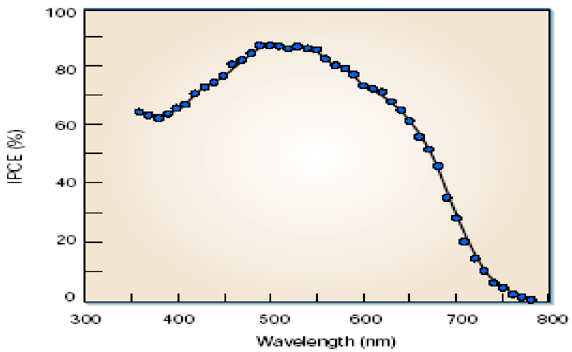
Cell efficiency

< Power conversion efficiency (η) >



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

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



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

F.F : Fill factor

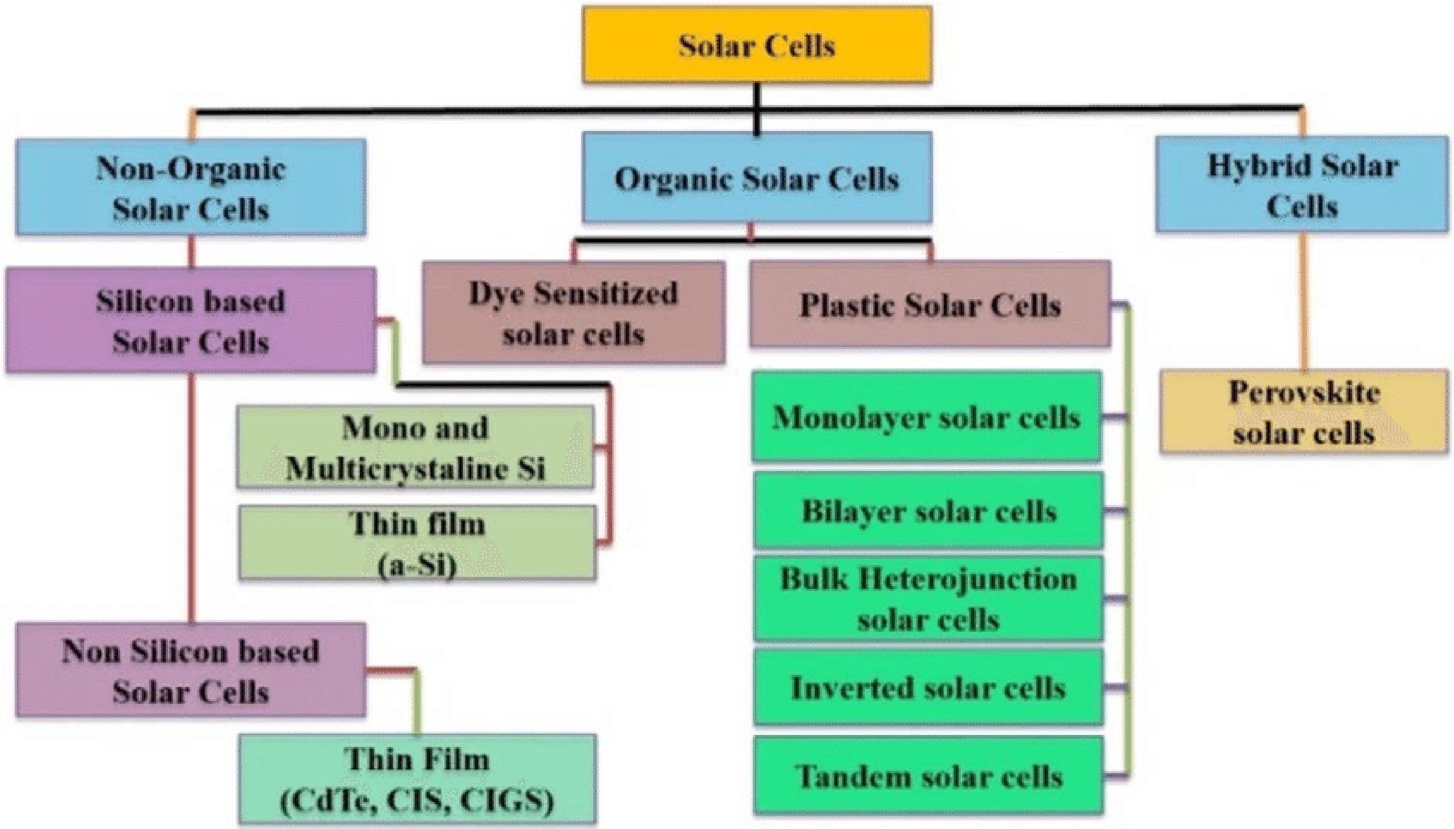
$$FF = \frac{I_{mp} V_{mp}}{I_{sc} V_{oc}}$$

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

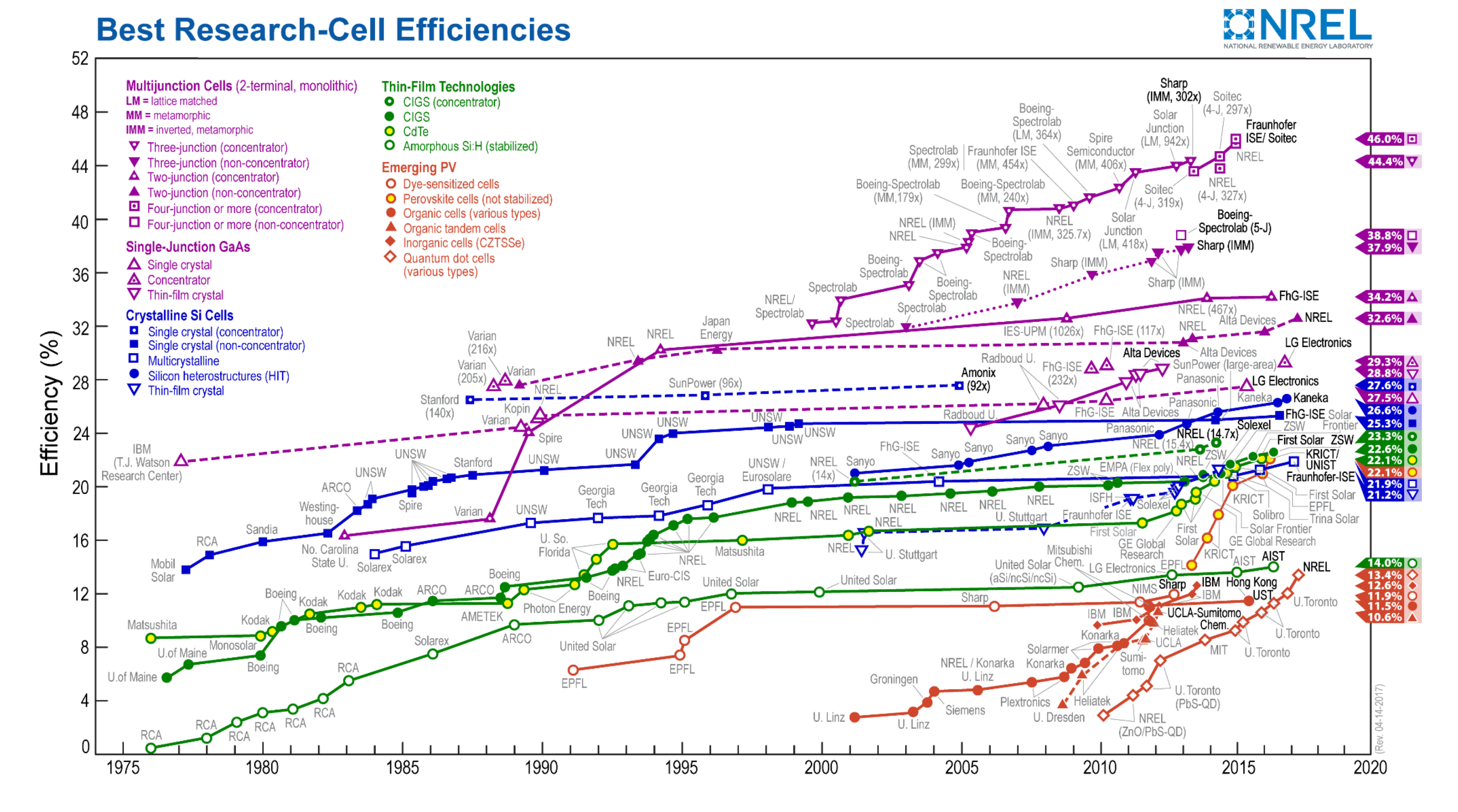
Under **AM 1.5G** simulated solar illumination

$$\boxed{\begin{aligned} IPCE &= \frac{\text{no. of electrons through the external circuit}}{\text{no. of photons incidnet}} \\ &= \frac{[1240\ eV\ nm][photocurrent\ density\ (\mu A\ cm^{-2})]}{[wavelength\ (nm)][irradiance\ (mW\ cm^{-2})]} \end{aligned}}$$

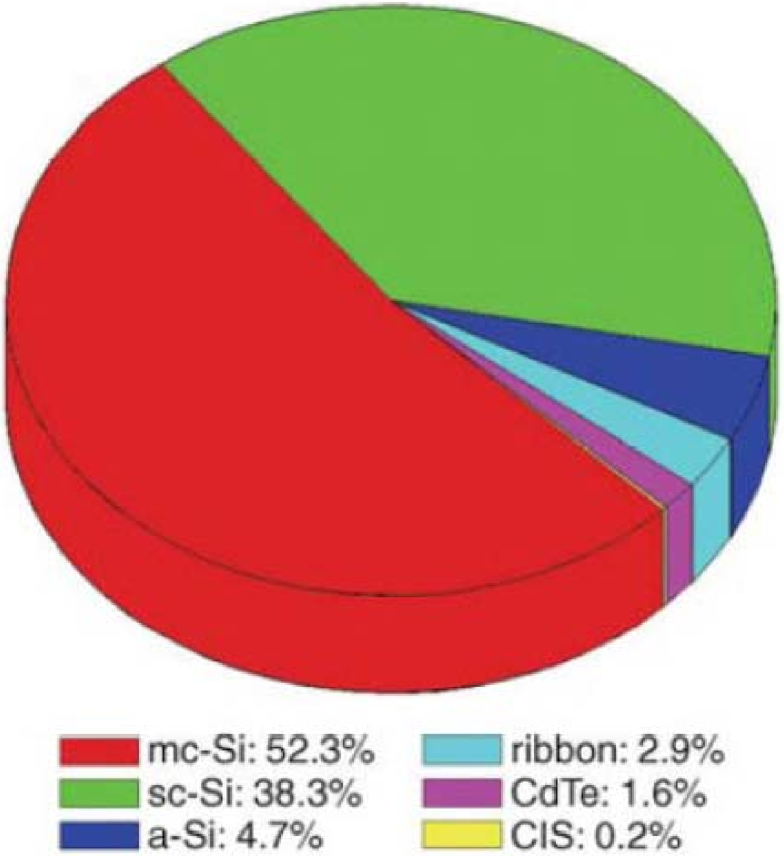
Classification of solar cells



PV efficiency

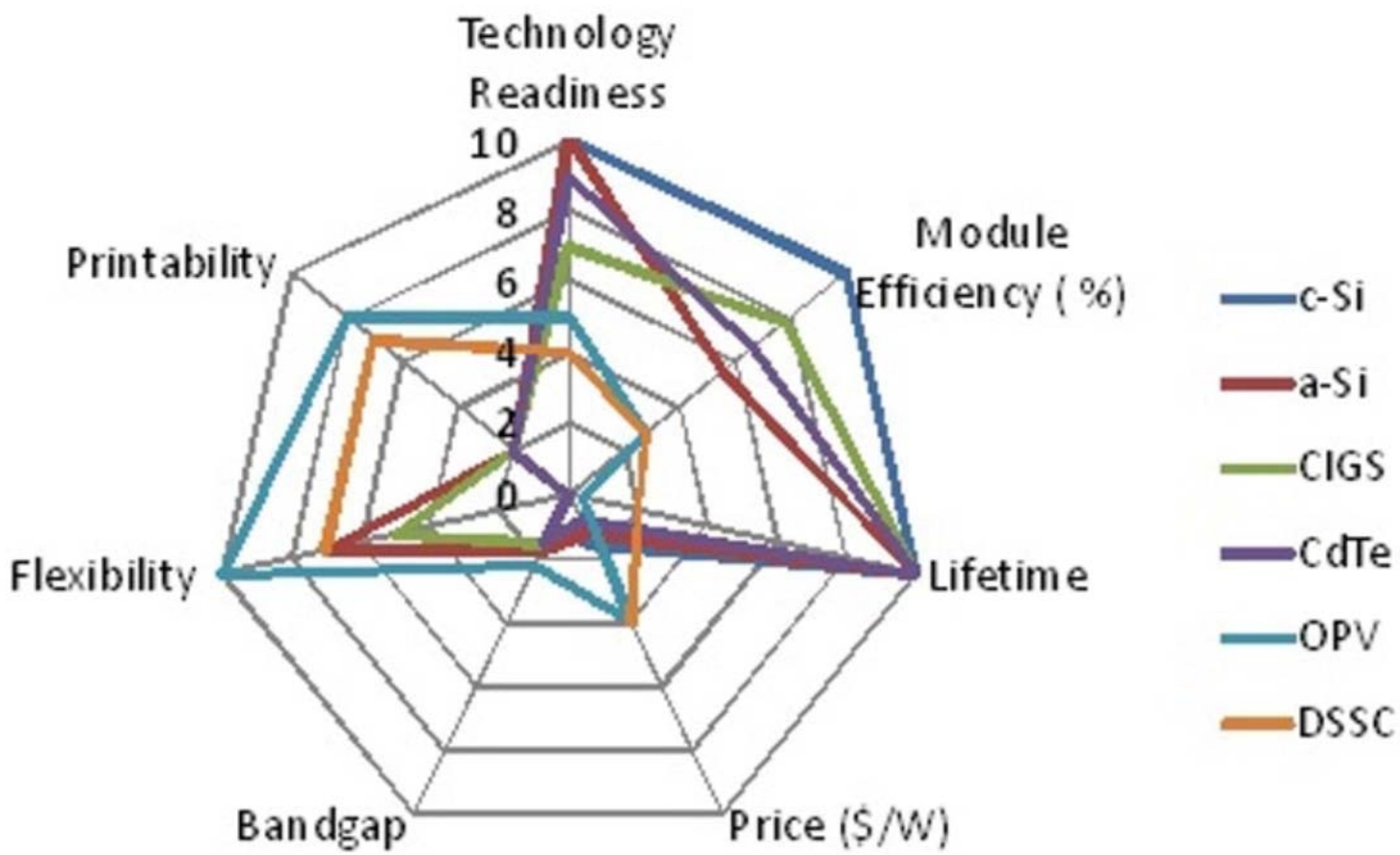


Distribution of solar cell production by materials



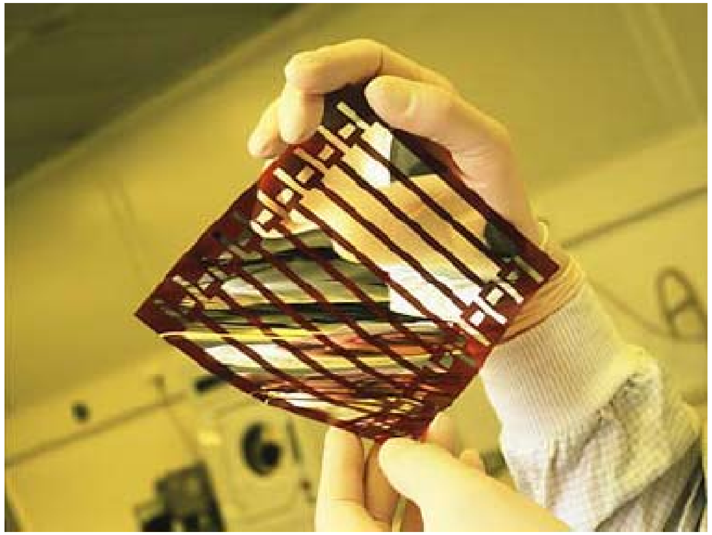
Solar cell materials are dominated by Si (98.2%)

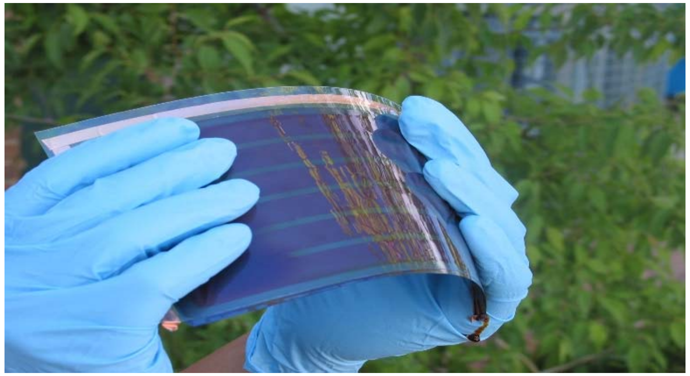
Various kinds of solar cells



Why OPVs?

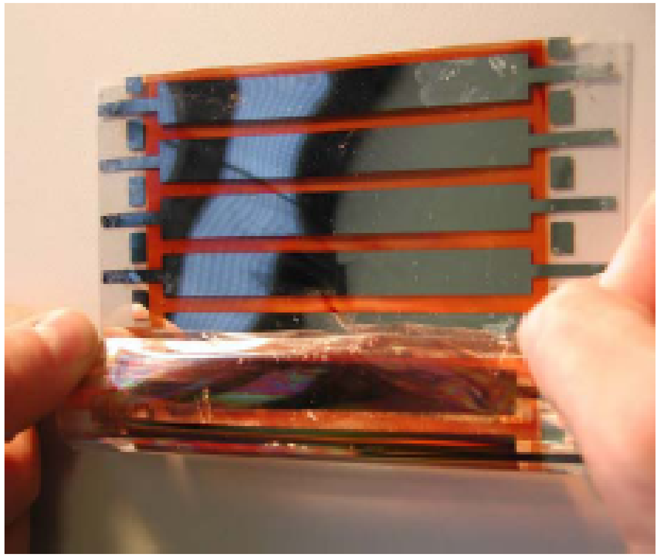
Advantages of Organic PVs (OPVs)
- -Processed easily over large area using
  - -spin-coating
  - -doctor blade techniques (wet-processing)
  - -evaporation through a mask (dry processing)
  - -printing
- -Low cost
- -Low weight
- -Mechanical flexibility and transparency
- -Band gap of organic materials can be easily tuned chemically by incorporation of different functional group





Why OPVs?

- OPV shows a promising technological development – efficiencies at 5 % level, no obstacles identified for 10 %
- The usage of reel to reel printing technologies guarantees a favorable cost structure
- The PV market demands low cost flexible solutions
- The energy market demands portable, decentralized renewable energies



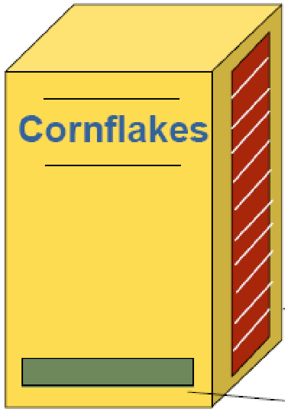
➡ OPV is the most promising candidate for a next generation PV

Source: Siemens AG

Why OPVs?

Polymer Solar Cells Applications

- The low cost of plastic PV may enable solar power in applications where it was previously un-economic
- Disposable solar powered products become a reality
- Flexible and conformable PVs can be integrated more easily into 'soft' or non-planar packaging
- Large-area, flexible solar panels could be used to make solar tents, solar sails, portable solar power modules



OPV applications

Energy Sunbag

- 1.5W under 1 sun
- Battery: 2000mAh (Input: 5.0~5.5V, 500mA, Weight: 61g)
- Bag size: 37X29X13cm³

149,00 €
(incl. 19 % MwSt.)

* http://www.energy-sunbags.de

5% PCE OPV
: 10mA/cm² X 0.5V ➔ **5 mW/cm²**

Lithium Battery for Cell Phone
: **3.7V, 1000mAh** ➔ **3700 mWh**
= **740 cm²** **area** (5% PCE OPVC)

A4 size (29.7 X 21 = 623.7 cm²) X 2
= 1247.4 cm²

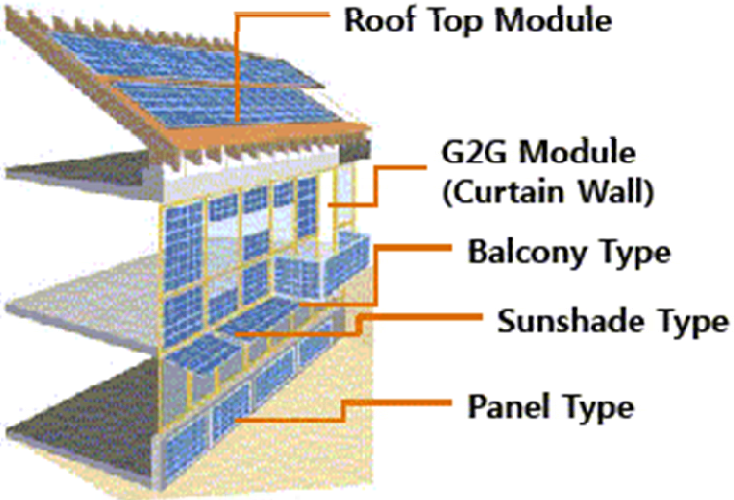
Aperture Ratio ~ 0.60 ➔ **748.44 cm²**

**2장의 A4크기의 OPV를 이용하면,
1시간 안에 휴대폰을 완충할 수 있다?**

OPV applications

OPV systems

<대규모 발전 설비>



<에너지 자립형 건물>

OPV systems

OPV systems

OPV in building

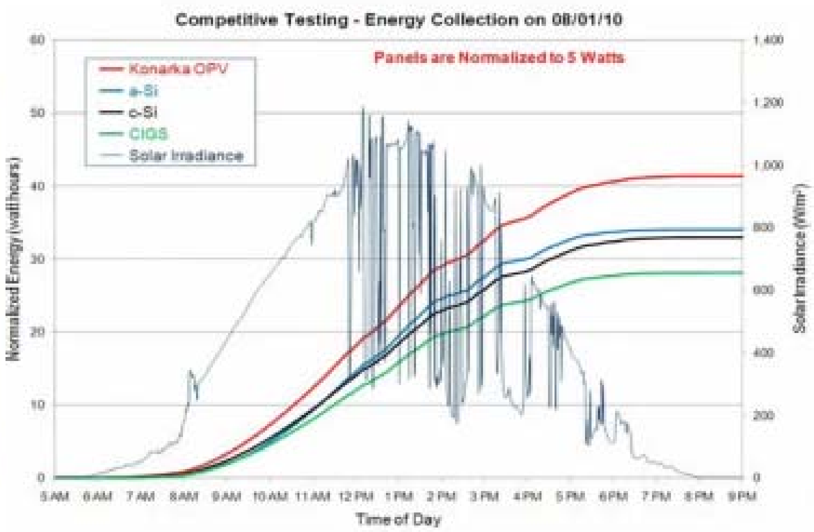

Big bubble bag (Italy)

Roof of Bus Shelter (San Francisco)

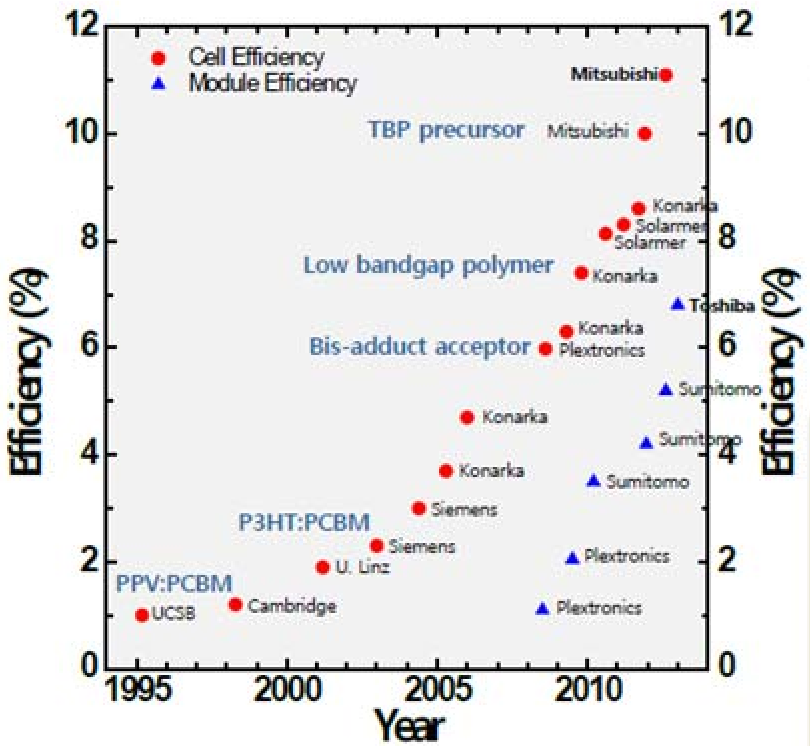

Greenhouse (NH)


Carports (Florida)


Curtain Wall Installation (Florida)



OPV efficiency



	2012	2013	2014	2015	2016	2017	2018	2019
Commercial OPV Efficiency (%)	4.2	4.4	4.6	4.9	5.1	5.4	5.6	5.9

~~Konarka (USA)~~
- ~~8.6% Newport 인증 (Nov. 2011)~~
- ~~2009년 2월 4W, 8W, 16W급 모듈 시제품~~

Plextronics (USA)
- 6.5% PCE (25cm², Nov, 2011)
- Cowork with IMEC, Solvay

Solarmer Energy (USA)
- Y. Yang 교수 Spin off
- 9.31% (Aug, 2012)
- 10.6%@0.103cm², Tandem (Y. Yang, Sumitomo)
- 3.5% module (208.4cm², Jul, 2009)

Mitsubishi Chemical (Japan)
- **10.7%** (@1.03cm², 2012)
- **11.1%** (@0.159cm², 2012)
- `15년 15% 목표

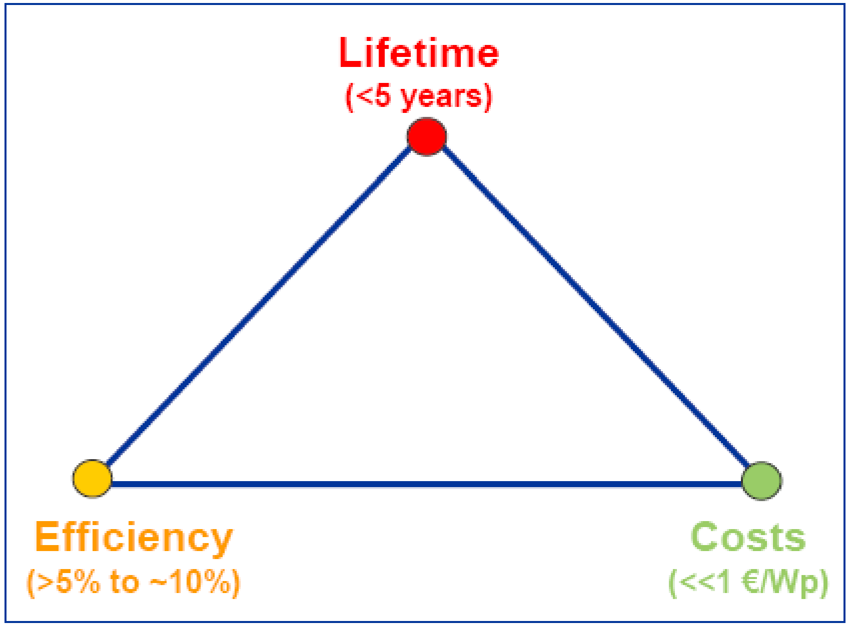
Sumitomo (Japan)
- 10.6% PCE (2013)
- 5.2%@294.5cm², 15 series (Apr. 2012) (0.689V, 11.73mA/cm², 0.642)

Toshiba (Japan)
- **6.8%@395.9cm²** (Sep. 2012)

Kolon (Korea)
- R2R Processed Flexible OPVs
- **11%** (0.09 cm², May, 2013)
- ~4% module (@60cm²)

Requirements of OPVs for commercialization

Parameters & technological goals



- The most important parameters of every solar technology are efficiency, lifetimes and costs
- The actual application defines which parameter or combination of parameters are more or less important
- Other OPV features like flexibility, weight, transparency are not sufficient to constitute a relevant competitive advantage

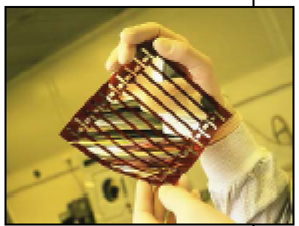
- Applications define relevant OPV parameters
- In the medium term there is no direct competition with Silicon

Source: Siemens AG

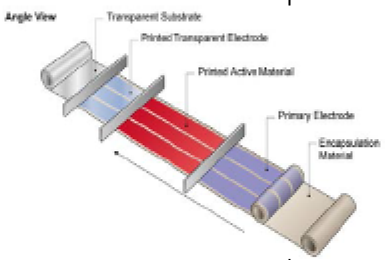
Requirements of OPVs for commercialization

Flexible OPVCs Technology

- **Power Conversion Efficiency** — ~10%
  - **Low-bandgap** Donors — ~1.4 eV
  - **High LUMO** Acceptors — ΔE > 0.3 eV
  - D-A Nanomolpology control — Bulk Heterojunction
  - Organic Multijunction — Tandem, Stack
  - **Buffer Layer**



- **Device Stability** — >5 years
  - Opti-/Thermally **Stable** Materials
  - **Nanomorphology** Stabilization — Self-Organizable Mater.
  - High Barrier Flexible Substrate — OLED Tech.
  - Encapsulation/Passivation — OLED Tech.



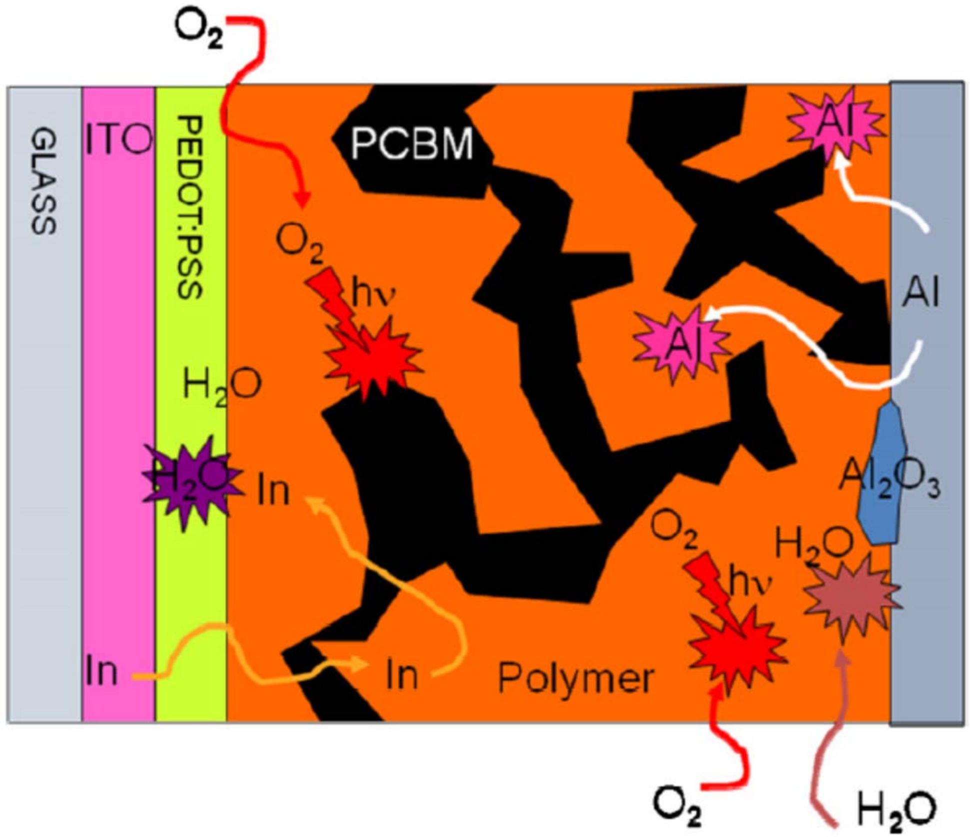
- **Manufacturing Technology** — <0.5$/Wp
  - **Printing Technology** — Gravure, Inkjet, Aerosol-Jet
  - **R2R** Processibility — Flexible substrate

Reliability

• Encapsulation will be needed.

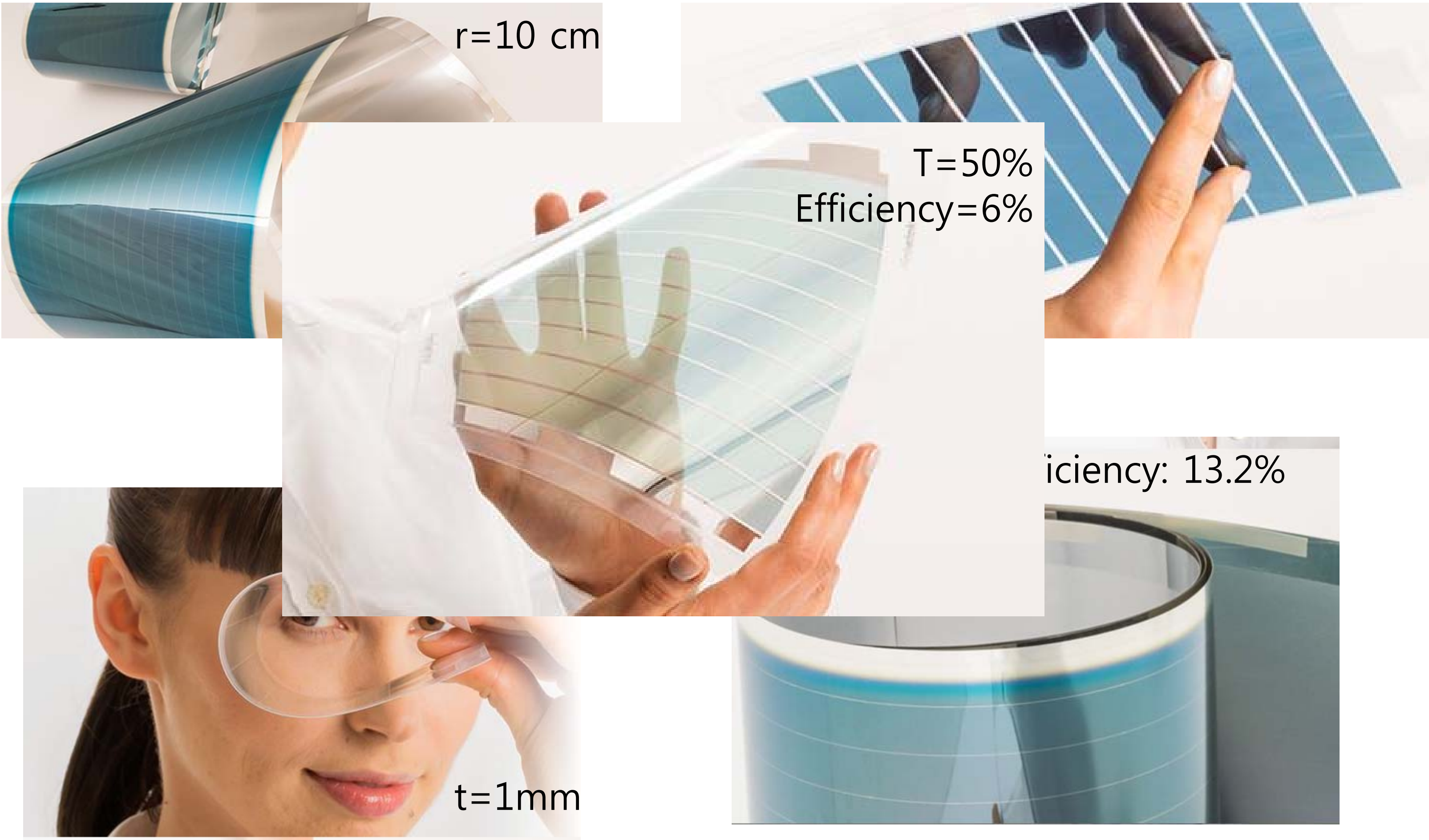
• A UV filter will probably be needed.

• Many molecules are very stable in light.



F.C. Krebs, et al., Solar Energy Materials (2008)

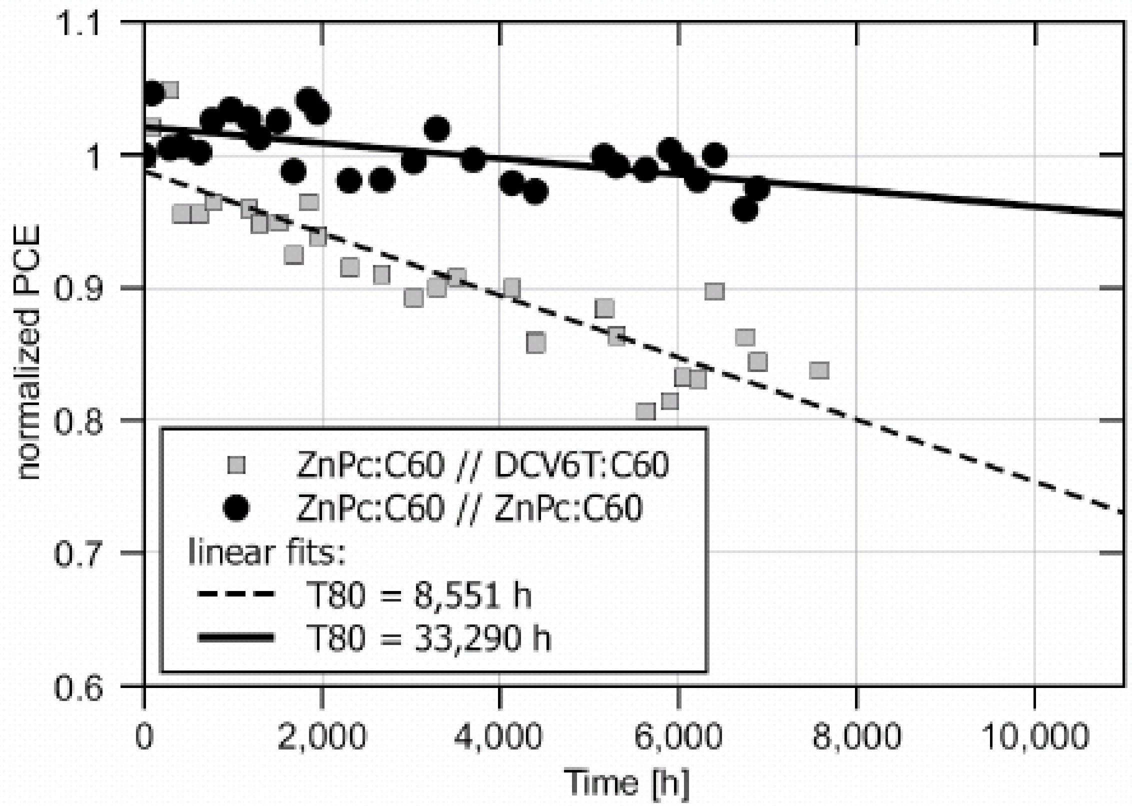
Leading research group (Heliatek)



Heliatek reliability study

Light intensity
2.2 suns

Temperature
48 °C



(33,290 hrs)(2.2)= 73,000 hrs or **8.4 years continuous use**

At 5 hrs/day of peak sunlight, the **lifetime is 40 years**.

Semiconductor polymers

- 1977: discovery of electrical conductivity in doped polyacetylene
- 1986: Organic Photovoltaic Cell (OPV), C. W. Tang (Kodak)
- 1986: Organic Field-Effect Transistor (OFET), H. Koezuka (Mitsubishi)
- 1987: Organic Light-Emitting Diode (OLED), C. W. Tang (Kodak)
- 2000: Nobel prize in Chemistry for A. Heeger, A. McDiarmid, H. Shirakawa

Alan J. Heeger **Alan G. MacDiarmid** **Hideki Shirakawa**

그림 1. 전도성 고분자를 개발한 2000년 노벨화학상 수상자들

Inorganic semiconductor

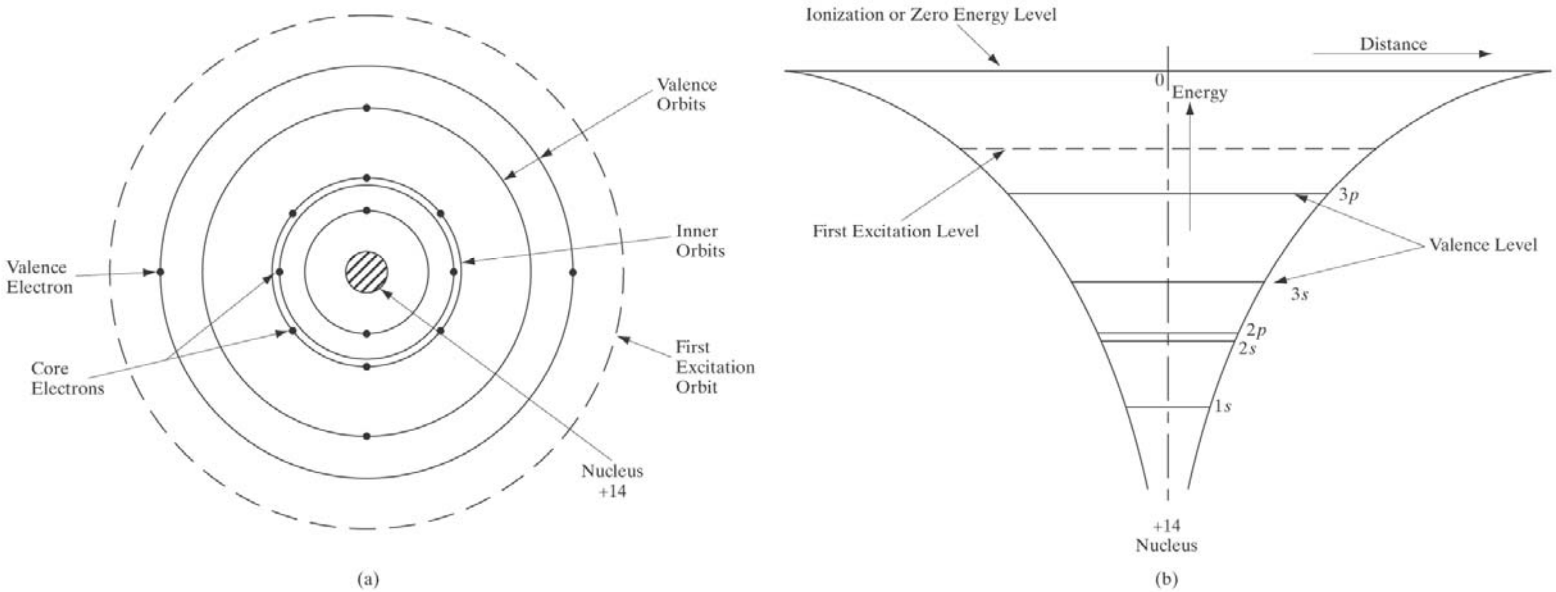
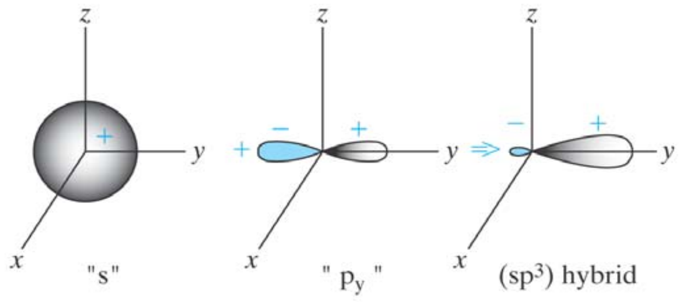


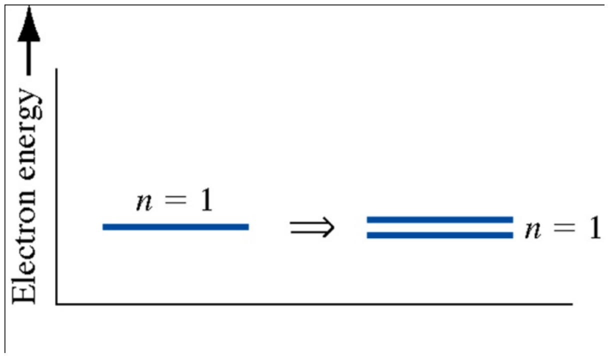
Figure 2.8

Electronic structure and energy levels in a Si atom: (a) The orbital model of a Si atom showing the 10 core electrons (**n** = 1 and 2), and the 4 valence electrons (**n** = 3); (b) energy levels in the coulombic potential of the nucleus are also shown schematically.

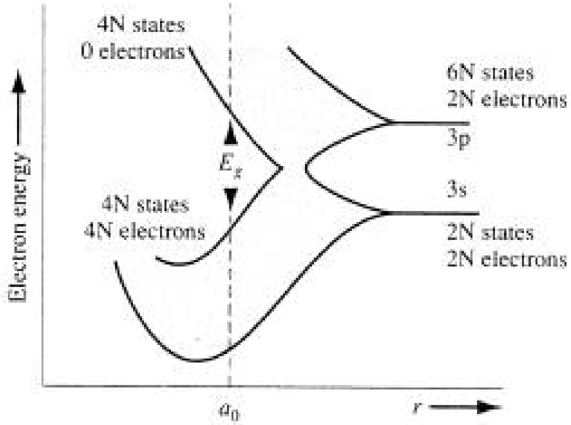
Inorganic semiconductor



- Interestingly, in a Si crystal when we bring individual atoms very close together, the *s*- and *p*-orbitals overlap so much that they lose their distinct character, and lead to four mixed *sp*^{3} orbitals



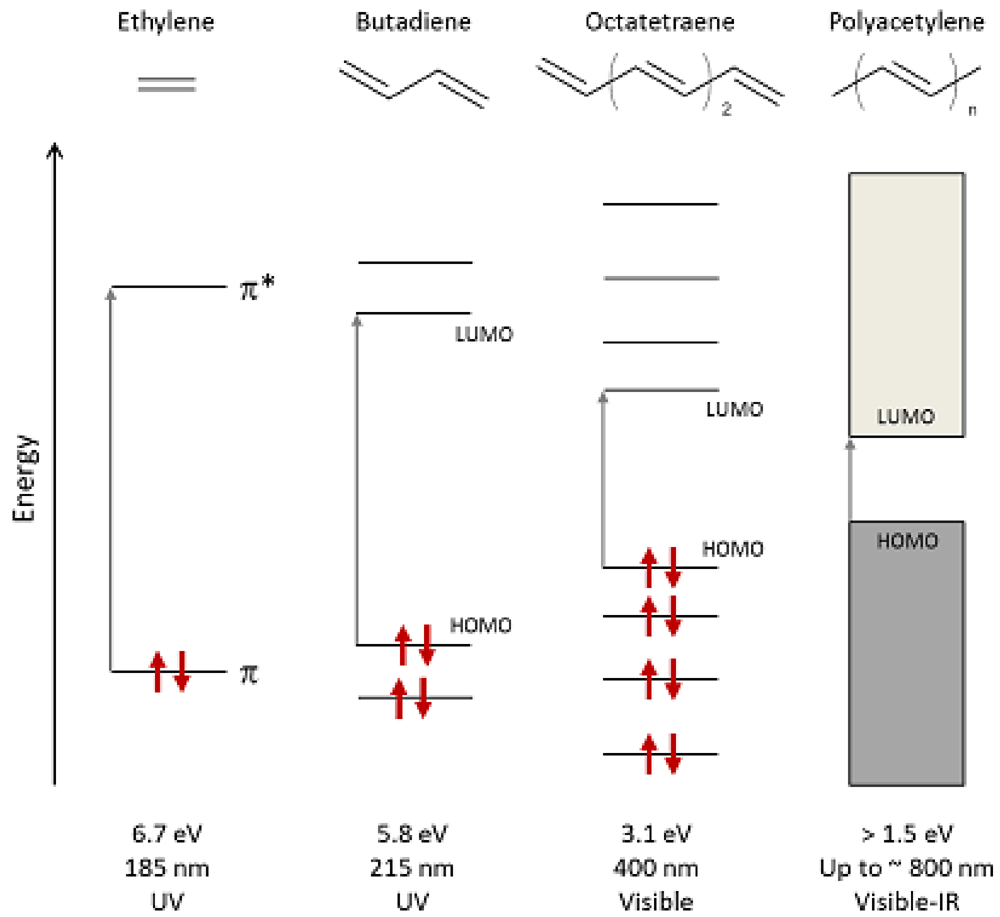
The splitting of the n=1 state



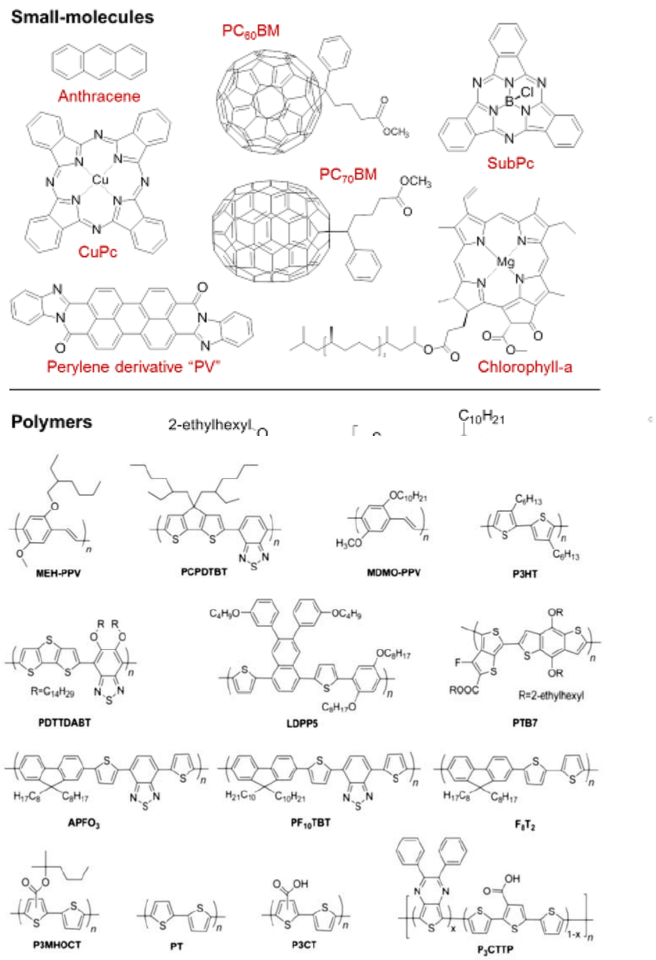
Pauli exclusion principle

"No two electrons can have the same quantum number"

Organic semiconductors

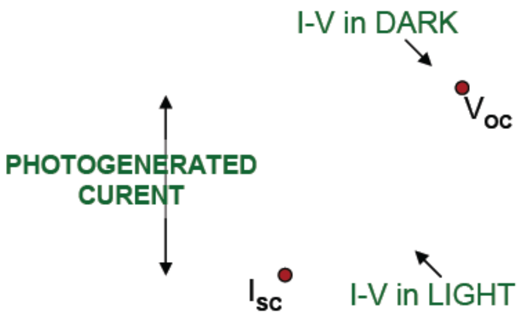


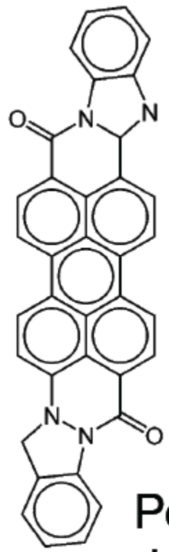
Organic semiconductors materials



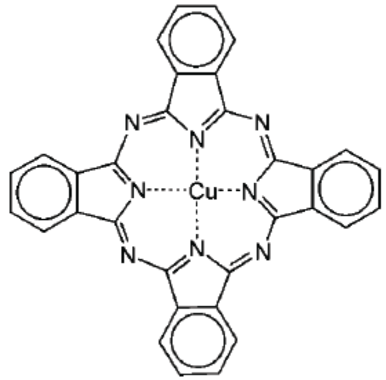
1st organic solar cell

Power conversion efficiency ~ 1%

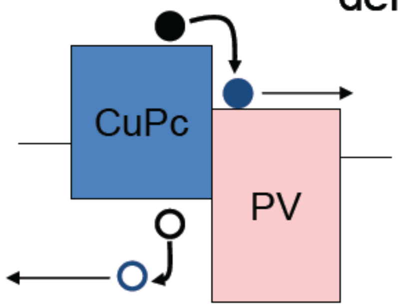




Perylene tetracarboxylic derivative (PV)



CuPc



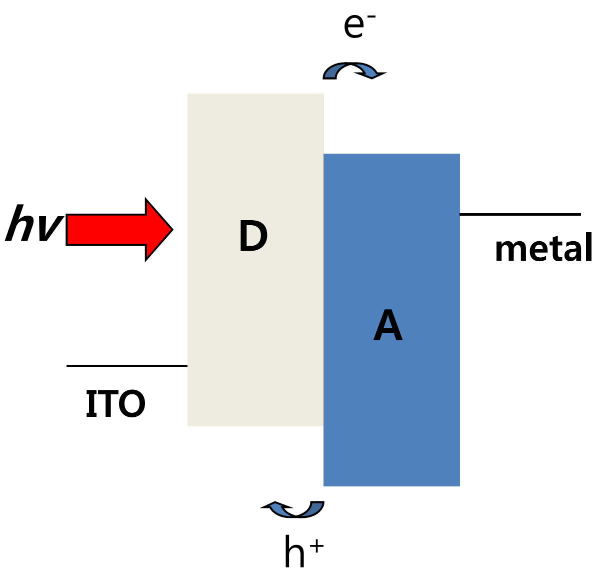
Need interface to maximize exciton dissociation

Courtesy of

V_{OC} = open-circuit voltage

I_{SC} = short-circuit current

PV effect in conjugated polymer



- Light is absorbed in the polymer layer
- Absorption creates a bound electron-hole pair (exciton)
- Exciton is split into separate charges which are collected at contacts

- Exciton must be seperated so that a photocurrent can be collected.
- Excitons dissociated by electron transfer to an **acceptor** material, or hole transfer to a **donor**.
- Simplest approach is to make a **donor-acceptor heterojunction**