2.626 Fundamentals of Photovoltaics
Fall 2008

Review: Crystalline Silicon and Thin Film PV Technologies

Lecture 12 – 2.626

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General Matters

- Class Project Next Steps
- Concept Quiz

2.626 – Fundamentals of Photovoltaics

Concept Quiz #4 – October 21, 2008

Question #1:

List the name of one wafer-based and one thin film PV technology in commercial production today.

Question #2:

List one major advantage and one major disadvantage of each technology.

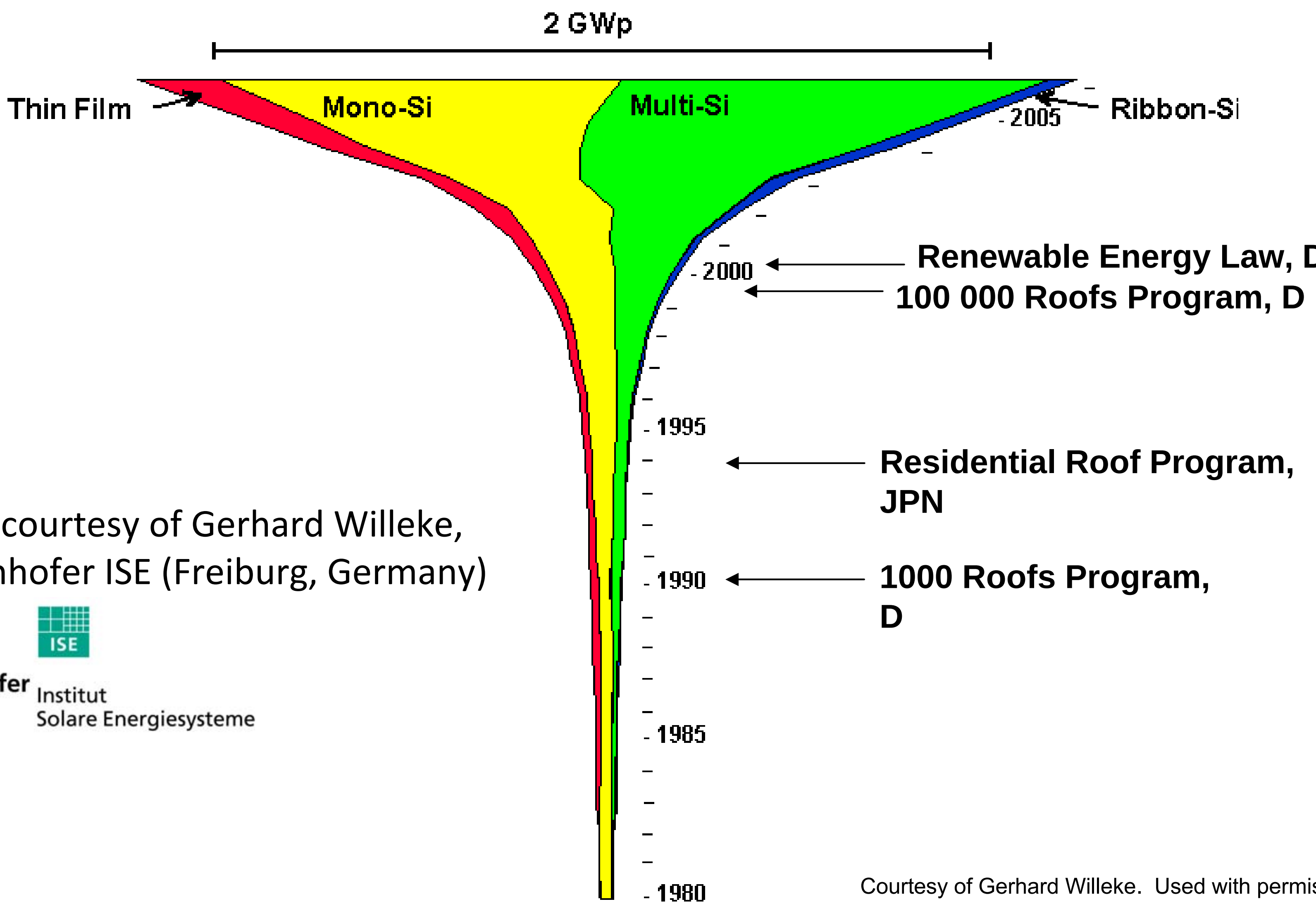
Question #3:

List one "next generation" PV technology, and explain how it has the potential to overcome the limitations of technologies in commercial production today.

Summary of the Most Common Commercial and Nearly-Commercial PV Technologies

		Common Deposition/Growth Method	Sample Companies	Typical Commercial Cell Efficiencies
	Monocrystalline Silicon (sc-Si)	Czochralski (CZ)	SunPower, REC, Sanyo…	17-22%
	Multicrystalline Silicon (mc-Si)	Directional solidification (Bridgman)	Q-Cells, Suntech, REC, Solarworld…	15.5-16.5%
	Ribbon Silicon	String Ribbon (SR) and Edge-defined Film-fed Growth (EFG)	Evergreen Solar, SCHOTT Solar, Ever-Q…	~15.5%
	Cadmium Telluride (CdTe)	Chemical vapor deposition (CVD) on glass	First Solar...	~11%
	Amorphous Silicon (a-Si) and variants	Plasma-enhanced chemical vapor deposition (PECVD) on glass or metal substrates	Energy Conversion Devices, Oerlikon, Applied Materials…	~6-9%
	Copper Indium Gallium Diselenide (CIGS)	Variety: CVD, physical vapor deposition (PVD) on glass, metals.	Numerous start-ups: Nanosolar, Miasolé, Heliovolt…	Pre-commercial: 6-10% reported.

Photovoltaics: Current Production



Slide courtesy of Gerhard Willeke, Fraunhofer ISE (Freiburg, Germany)

Fraunhofer Institut Solare Energiesysteme

Silicon is the second most abundant element on Earth after oxygen (28% of the Earth's crust). Its most familiar forms are sand and quartzite (the latter one is more pure).

Silicon in Nature: It's everywhere!

http://commons.wikimedia.org/wiki/File:Third_beach_sand.jpg

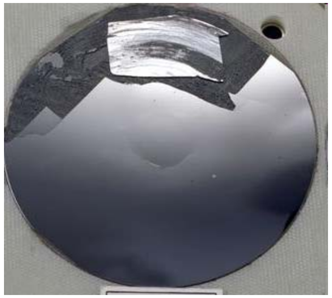
Human-made Monocrystalline Silicon

http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/materials/Czochralski_1.gif.

Human-made Multicrystalline Silicon

http://www.tkx.co.jp/english/solar/images/index_img_03.jpg

http://www.tkx.co.jp/english/solar/images/index_img_05.jpg



Monocrystalline Silicon

http://commons.wikimedia.org/wiki/File:Multicrystallinewafer_0001.jpg

Multicrystalline Silicon

Quiz: Multi or Mono?

Sample c-Si Systems

http://www.energysolar.org.uk/energy_solar_pics/11-mw-solar-power-plant.png
http://technology4life.files.wordpress.com/2008/01/jumilla_solar_farm.jpg
http://images.pennnet.com/articles/rew/cap/cap_0705rew_photo03_02.jpg

11 MW_p plant in Portugal

20 MW_p plant in Spain.

Bavaria, Germany

Sample c-Si Systems

http://www.iea-pvps.org/cases/images/nld_0109.jpg
http://www.wired.com/news/images/full/moscone_f.jpg
http://earth2tech.files.wordpress.com/2008/05/cudrefin_switzerlandashx.jpeg

675 kW_p system, Moscone Center, SF.

Amersfoort, Netherlands

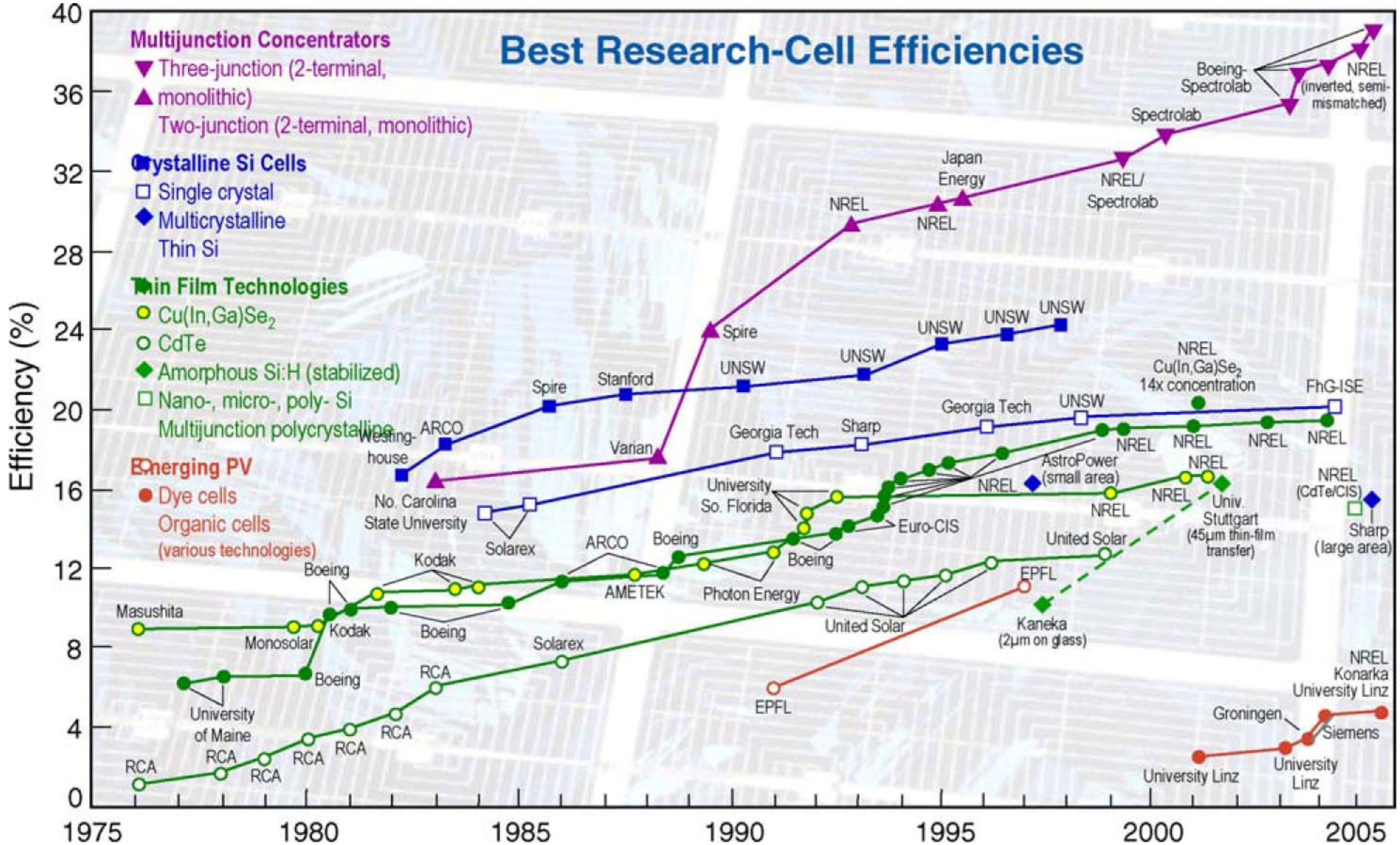
House in Rochester, NY

Sample c-Si Systems

Image removed due to copyright restrictions. Please see
http://www.smud.org/en/news/PublishingImages/IMG_0010.jpg

Zero energy homes, Rancho Cordova, CA
http://www.smud.org/news/multimedia.html

Record laboratory efficiencies of various materials



L.L. Kazmerski, Journal of Electron Spectroscopy and Related Phenomena 150 (2006) 105–135

Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

NOTE: These are record cell efficiencies under ideal conditions (25°C, ~1000 W/m^2)! Actual commercially-available silicon solar cells are typically 14-17% efficient. Modules are typically around 11-13%.

Thin Films

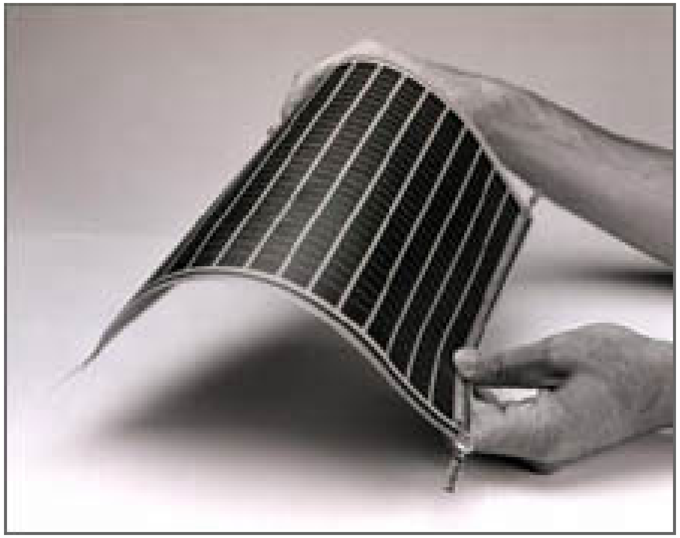
Advantages

- 1 µm layers ➔ less material used ➔ potential cost decrease.
- Potential for lower thermal budget ➔ potential cost decrease.
- Potential for roll-to-roll deposition on flexible substrate.
    - Technology transfer with TFT, flat panel display industry.
- Good for BIPV applications.
- Radiation hardness.

Disadvantages

- Lower efficiencies ➔ potentially larger module costs.
- Potential for capital-intensive production equipment.
- Potentially scarce elements sometimes used.
- Spatial uniformity a challenge during deposition.

Amorphous Silicon (a-Si)



Courtesy EERE.

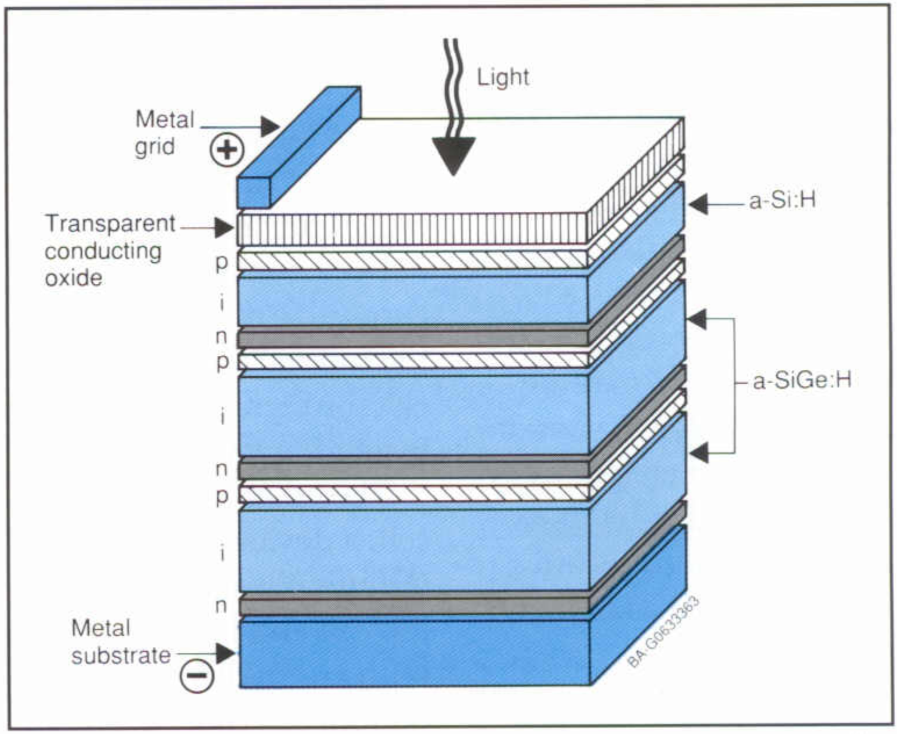
http://www.azom.com/work/Characterization%20of%20Photovoltaic%20Devices%20by%20Spectroscopic%20Ellipsometry%20Using%20Equipment%20From%20Horiba%20J_files/image006.gif

http://www.azonano.com/details.asp?ArticleId=2164

Advantages:
- Potentially very cheap, low-temperature.

Challenges:
- Overcoming the Staebler–Wronski effect (SWE)
- Uniform (thickness, quality, grain size) film deposition.
- TCO expensive.
- Challenges to scaling

a-Si heterostructures



B. Rech and H. Wagner, *Appl. Phys. A* **69** (1999) 155

Layers (variants of Si-based thin films) can include:

- amorphous silicon (a-Si)
- microcrystalline silicon (μc-Si)
- silicon germanium (SiGe)

CIGS and its variants

Image removed due to copyright restrictions. Please see
http://level2.phys.strath.ac.uk/SolarEnergy/img/intro.gif

http://level2.phys.strath.ac.uk

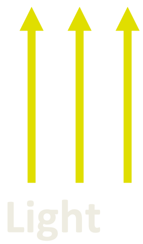
Main Advantage:
- Very high efficiencies (~20% lab).

Main Disadvantage:
- Challenge to deposit uniformly over large areas.

Cadmium Telluride (CdTe)

Image removed due to copyright restrictions. Please see Fig. 1 in Klein, A., et al. "Interfaces in Thin Film Solar Cells." *Record of the 31st IEEE Photovoltaic Specialists Conference* (2005): 205-210.

A. Klein, *Proc. 31st IEEE PVSC*
(Lake Buena Vista, FL, 2005) p.205



Main advantage:

- CVD technology well developed for application on glass.

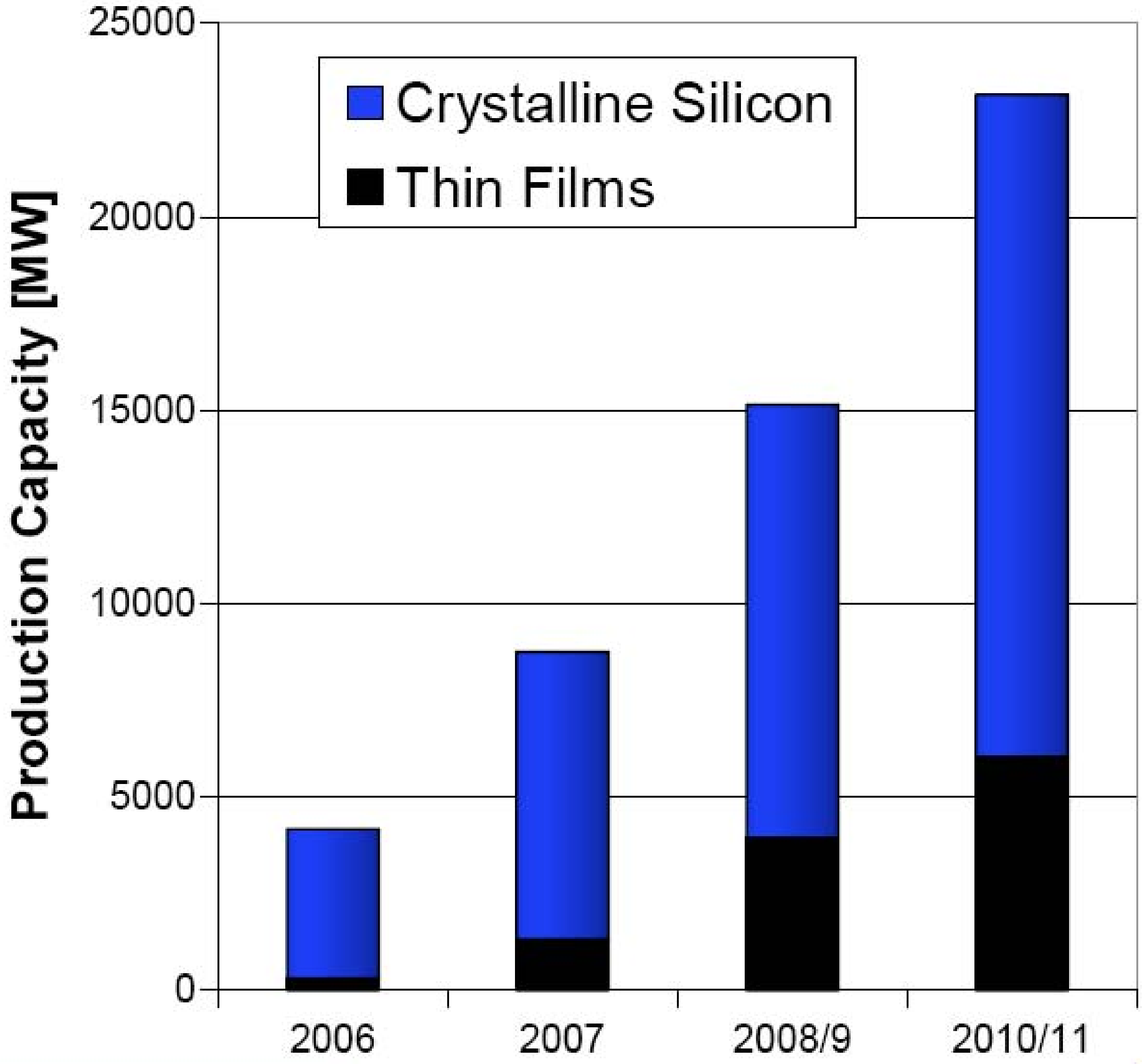
Main challenges:

- Cadmium: Marketability (Greenpeace opposed, banned in Japan)
- Tellurium: Natural abundance

CdTe Systems

by First Solar

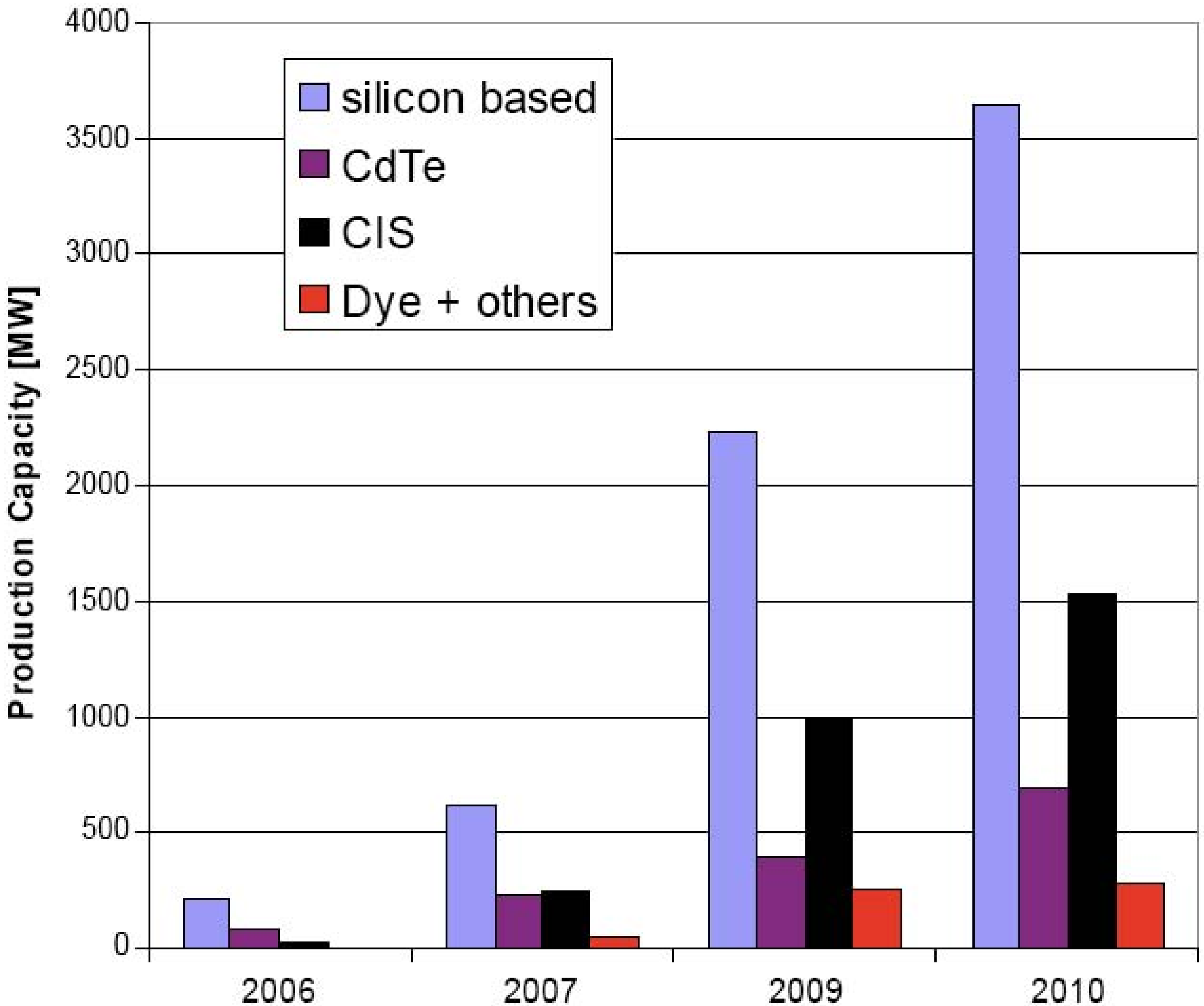
Announced Capacity Increases



Renewable Energies

Joint Research Centre

Announced Production Capacities by Technology



Renewable Energies

Summary of “Proto-Commercial” PV Technologies

		Common Deposition/Growth Method	Sample Companies	Typical Cell Efficiencies
High-Efficiency	Heterojunction solar cells	Heteroepitaxy	Spectrolab	40+%
	Gallium Arsenide	Chemical vapor deposition (CVD)	Concentrix	20-25%
Low Cost	Organics	Printing, spin-on coating		~2-5%
	Hybrid organic/inorganic	Printing, spin-on coating		~3-4%
	Dye-sensitized	Printing, spin-on coating		~4-8%

Tandem (Heterostructure) Cells

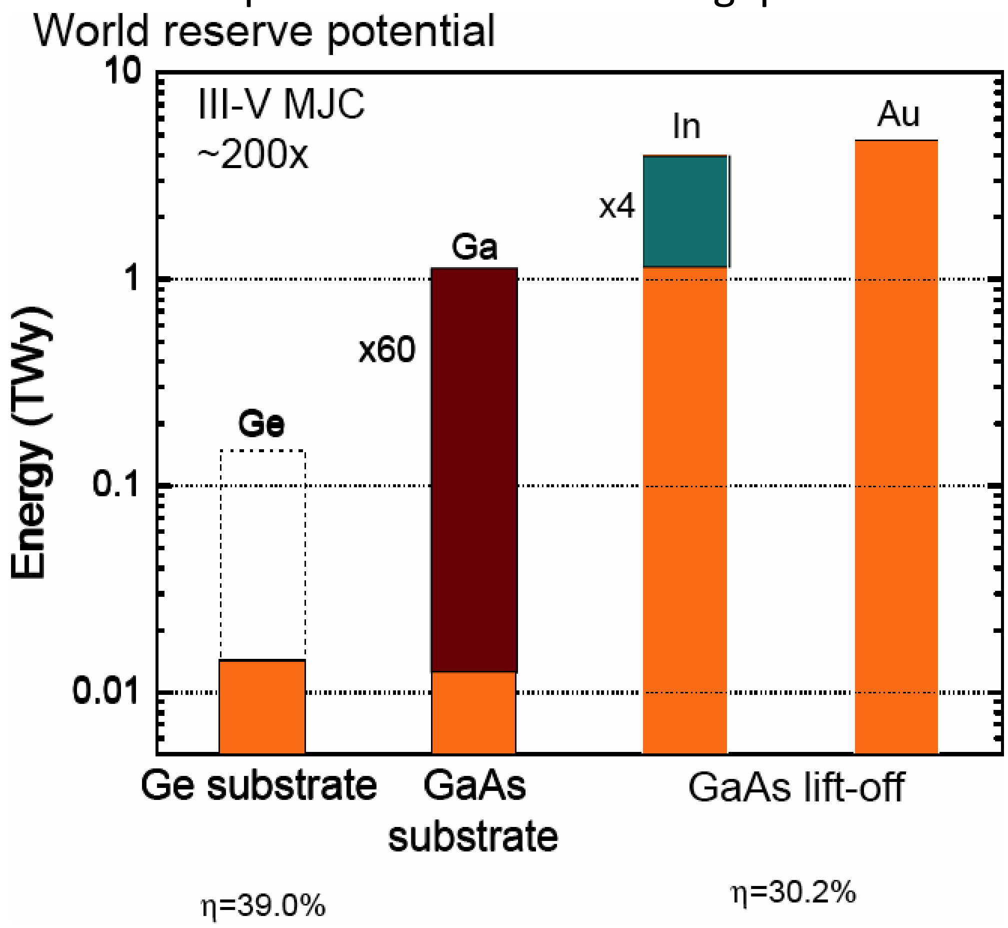
http://www.spectrolab.com/
DataSheets/TNJCell/utj3.pdf

- Stack of lattice-matched materials with decreasing bandgaps.
- Spectrolab Cells: $GaInP_2$/GaAs/Ge. Eff_{max}=40+% (under concentration).
- Theoretical efficiency limit for infinite tandem cell: 86.8%
- *Heteroepitaxial growth slow and expensive!*

Materials Availability

Most experts agree: not enough Ge to produce TW of PV.

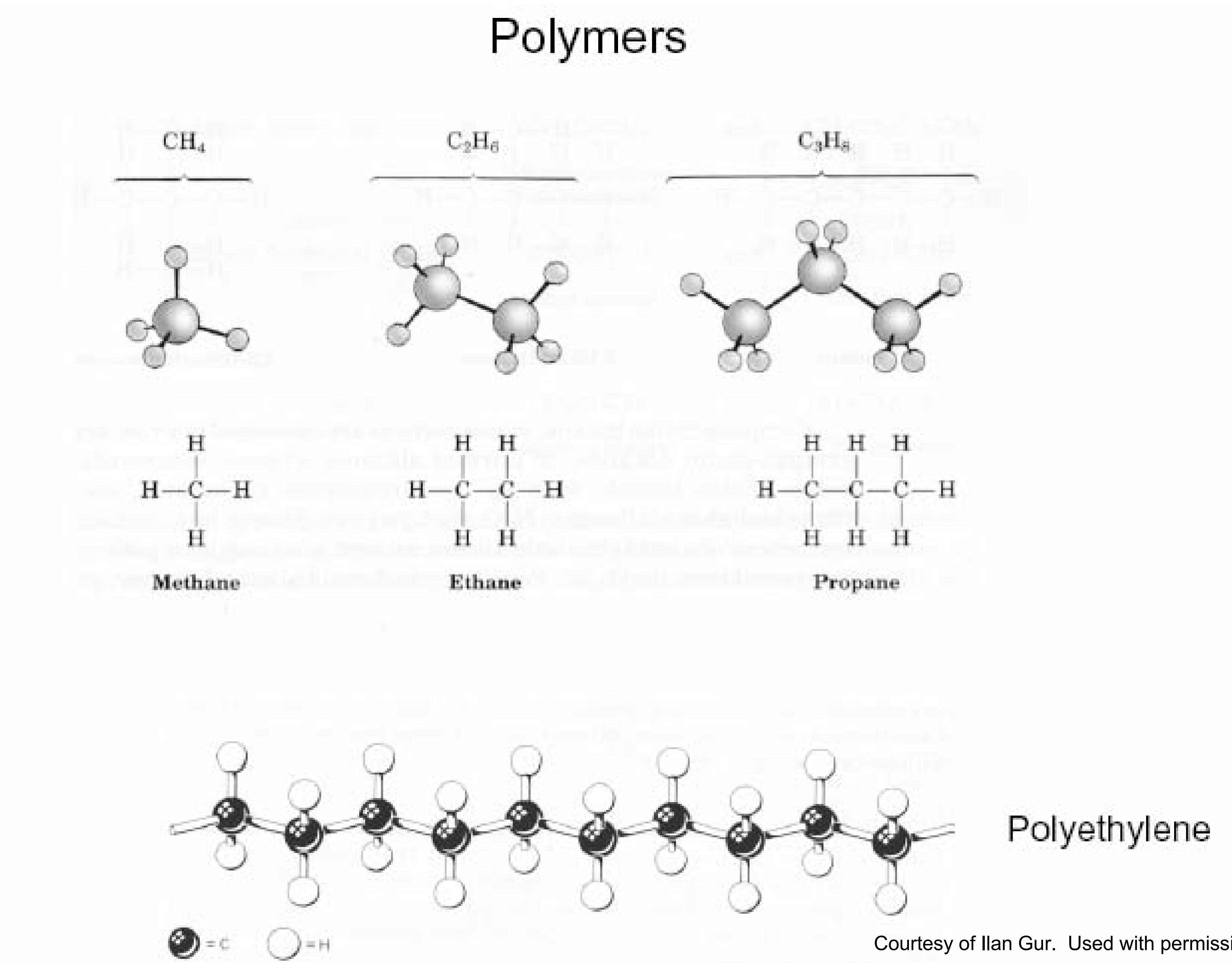
Development of new low-bandgap materials.



Source: Feltrin, A., A. Freundlich. "Material Considerations for Terawatt. Level Deployment of Photovoltaics." *Renewable Energy* 33 (2008): 180-185. Courtesy of Alex Freundlich. Used with permission.

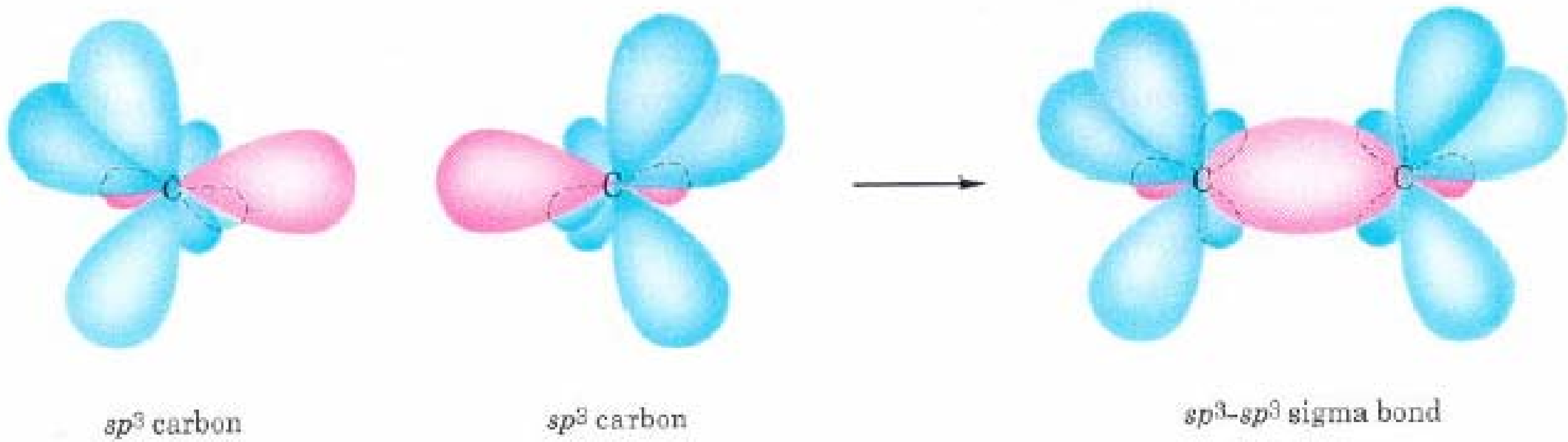
Alex Freundlich: http://www.rio6.com/proceedings/RIO6_181106_MA_1730_Freundlich.pdf

Organic Photovoltaics (o-PV)



Organic Photovoltaics (o-PV)

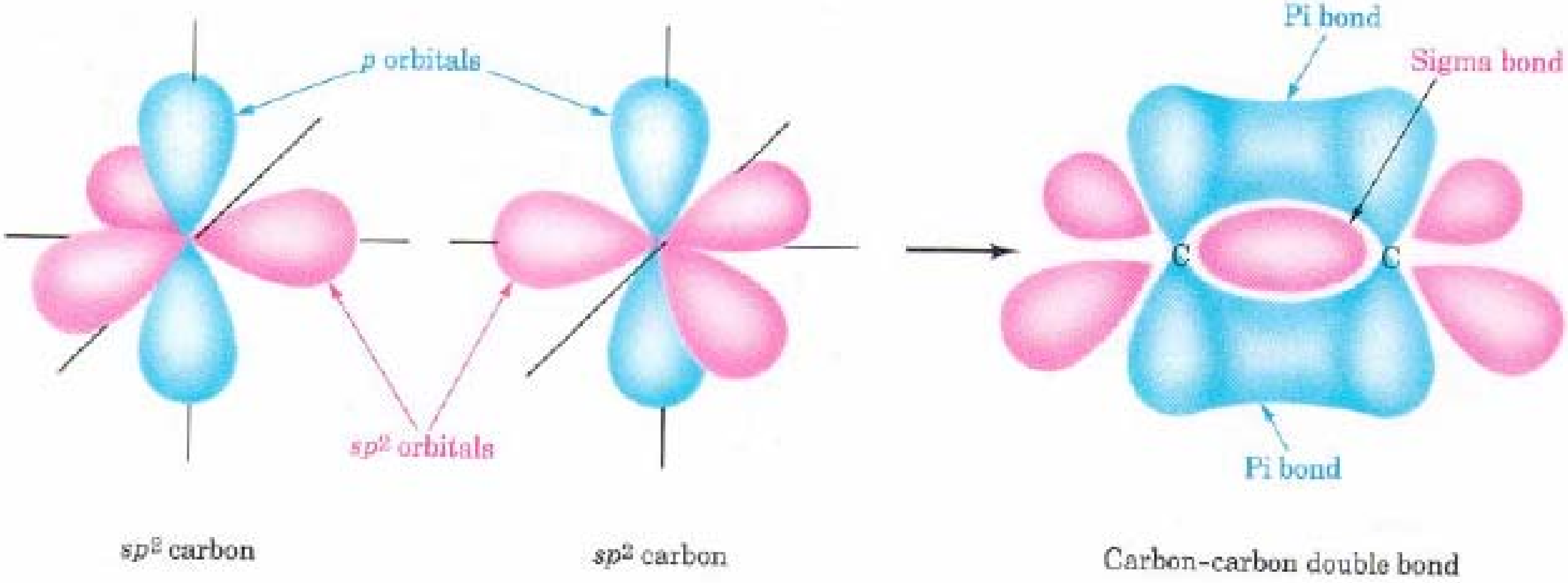
Why most polymers and organic solids are insulators



- sp^3 hybridized orbitals form sigma bonds.
- The electrons are highly localized.

Organic Photovoltaics (o-PV)

Why conjugated molecules can be semiconductors

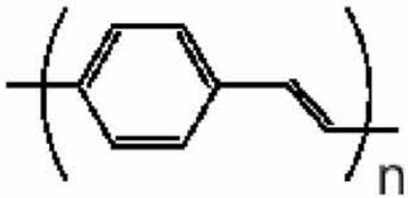


- p orbitals form π bonds.
- π electrons are more delocalized than σ electrons.

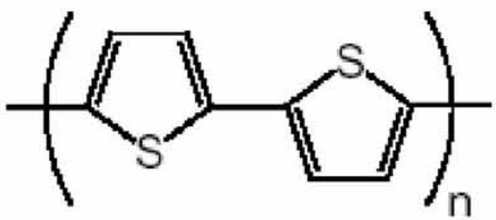
Organic Photovoltaics (o-PV)

Chemical structure of common conjugated polymers

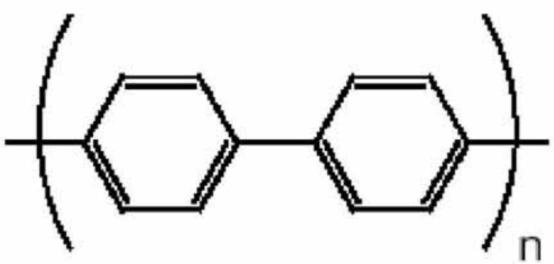
PA: polyacetylene
(1st conducting polymer)



PPV: poly(phenylene-vinylene)
(used in 1st polymer LED)



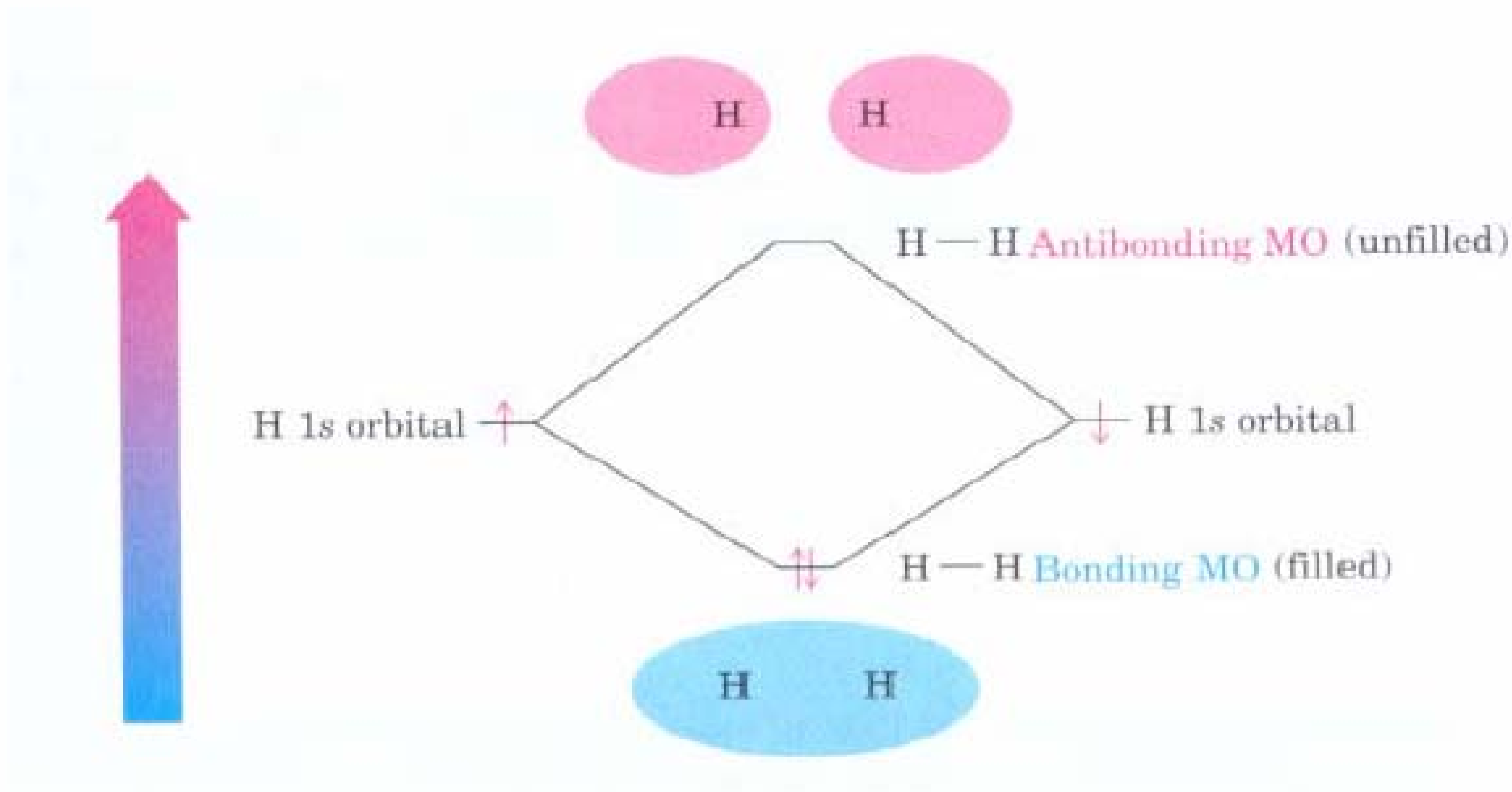
PT: polythiophene
(widely used in transistors)



PPP: poly(*para*-phenylene)
(large bandgap)

Organic Photovoltaics (o-PV)

Bonding and antibonding orbitals



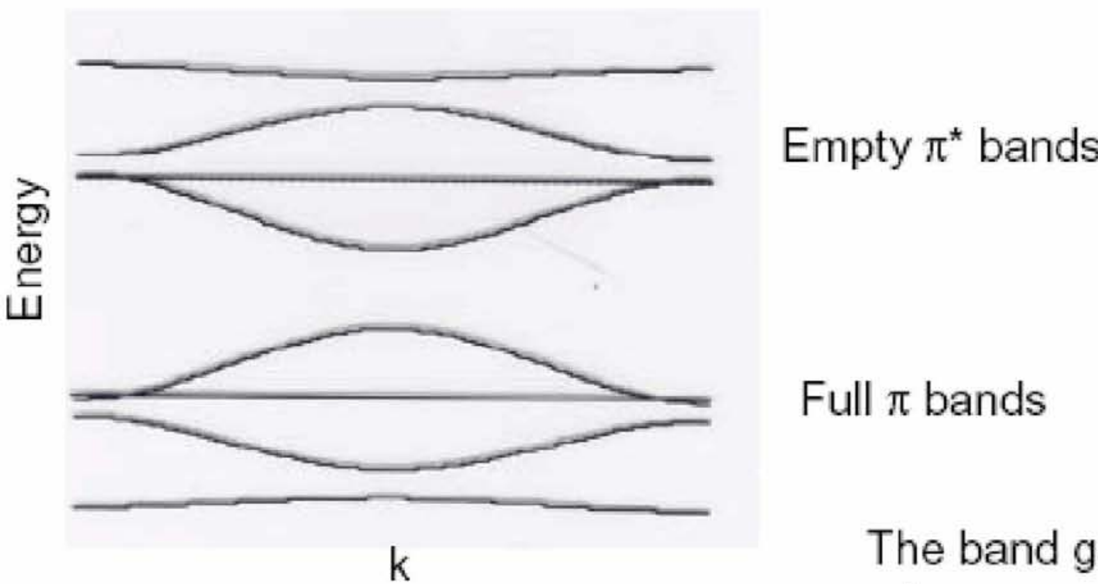
For a α bond, the energy gap is 6-12 eV.

For a π bond, the energy gap is 1-3 eV.

Organic Photovoltaics (o-PV)

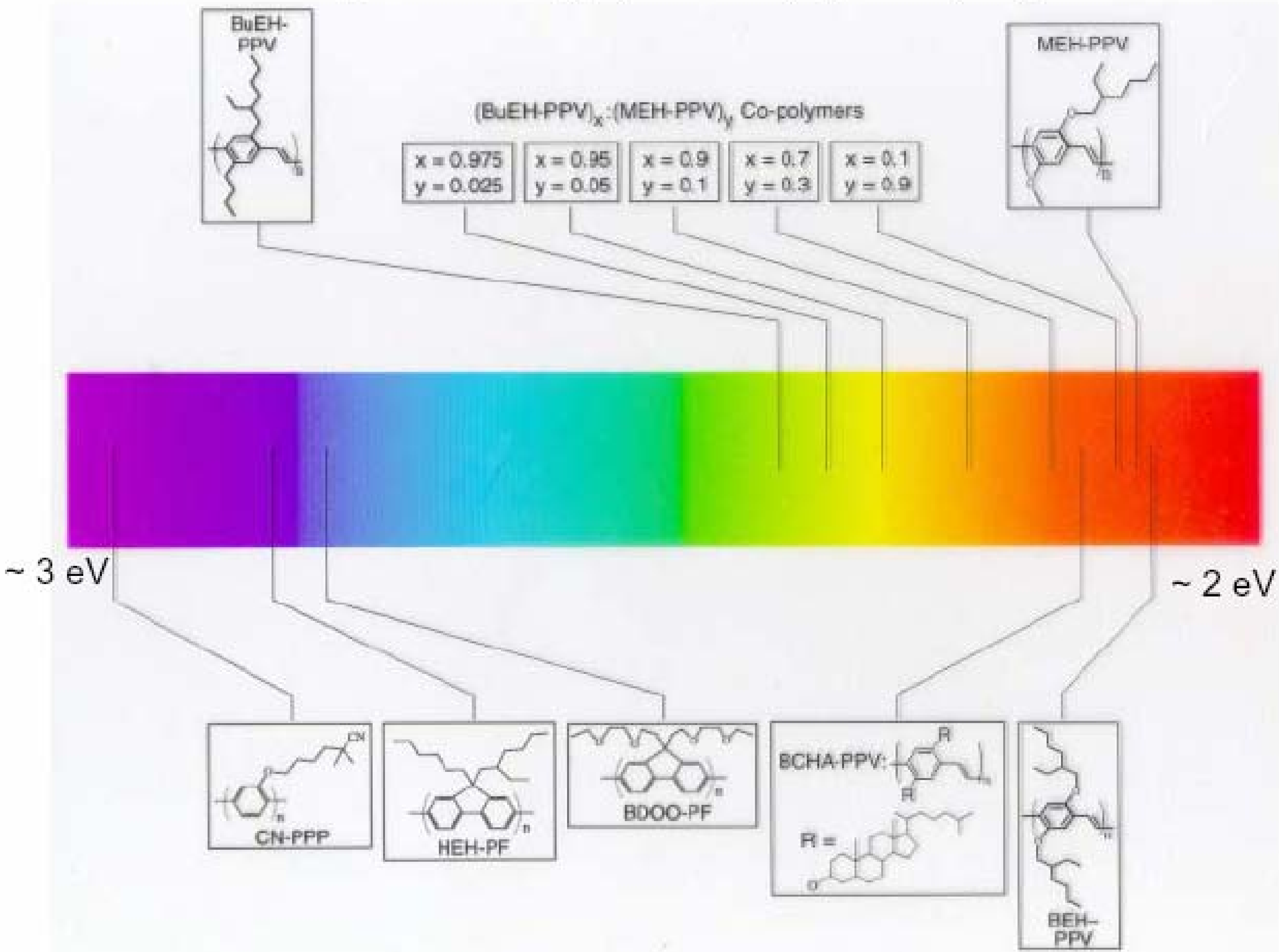
Band structure of conjugated polymers

Each p electron is the unit cell results in one π band.



The band gaps of conjugated polymers are in the range of 1 to 3 eV.

Tuning the bandgap of conjugated polymers



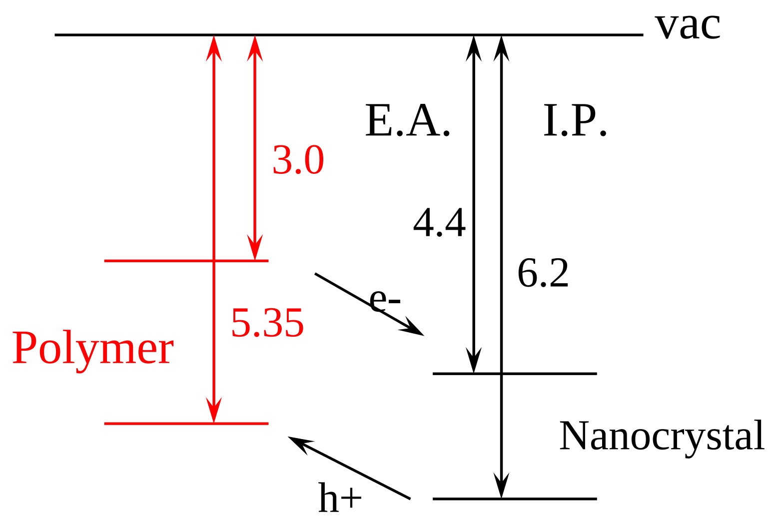
Pros and Cons of Organic PV

PROS:
- Cheap
- Low materials consumption
- Synthesis in solution, inkjet, screen printing, spin-on processes
- Bandgap tunable
- Low T annealing

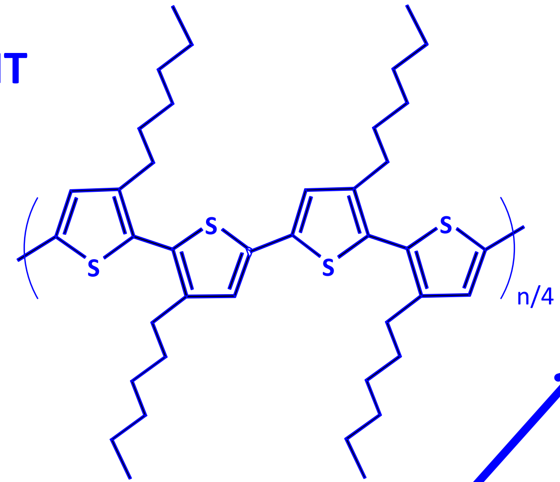
CONS:
- Low efficiency (low hole mobility: carrier hopping).
  Hot research area: High-mobility organics
- Most organic PV degrades when exposed to UV.
  Hot research area: Defect-tolerant and self-repairing materials

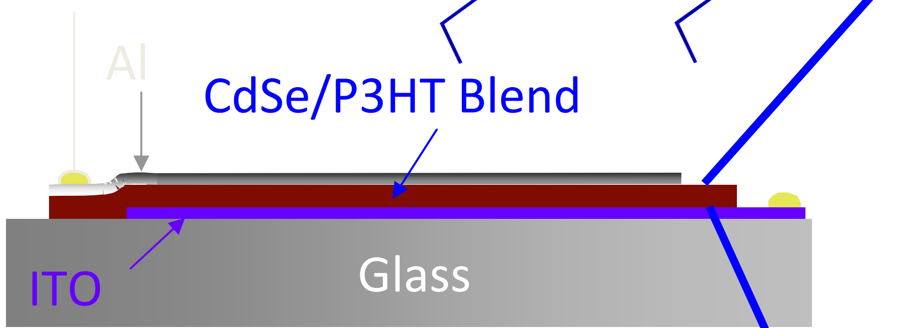
Further Reading:
Organic Photovoltaics: Concepts and Realization (Springer Series in Materials Science, Christoph Brabec, editor)

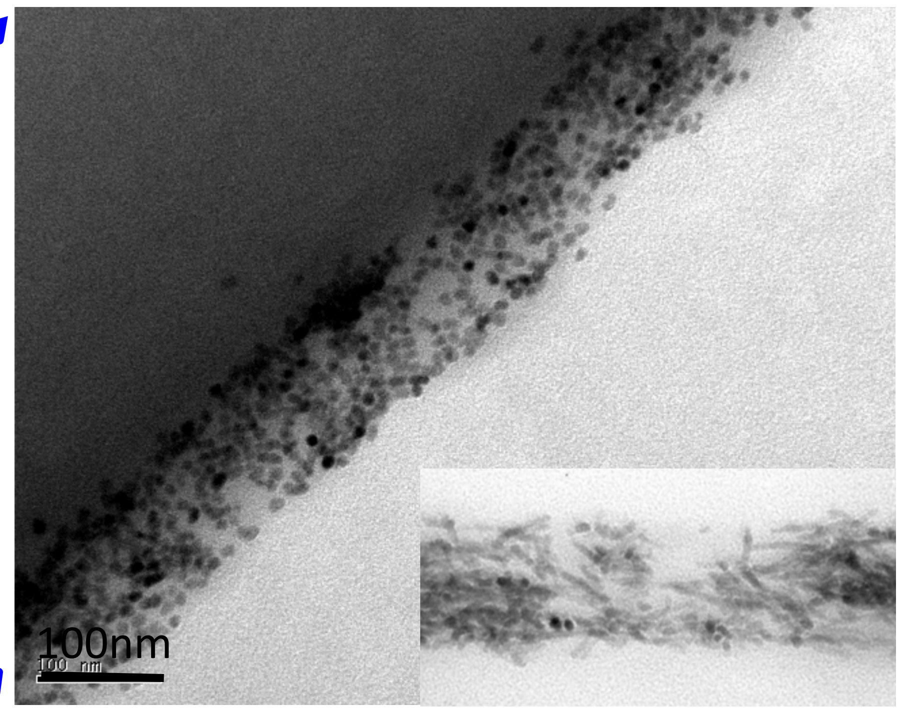
Nanocrystal Polymer Solar Cells



Regioregular P3HT







Hybrid Organic-Semiconductor

Images removed due to copyright restrictions. Please see:
Fig. 2 in Huynh, Wendy U., Janke J. Dittmer, and A. Paul Alivisatos. "Hybrid Nanorod-Polymer Solar Cells." *Science* 295 (2002): 2425-2427.

Fig. 8 in "Basic Research Needs for Solar Energy Utilization." *Report of the Basic Energy Sciences Workshop on Solar Energy Utilization*, April 18-21, 2005. http://www.er.doe.gov/bes/reports/files/SEU_rpt_print.pdf

CdSe nanocrystals: W.U. Huynh, *Science* **295** (2002) 2425

N. Lewis, *Science* **315** (2007) 798

Advantages:
- Synthesis in solution (e.g., inkjet)
- Bandgap tunable
- Spin-on process
- Low T annealing

Challenges:
- Low carrier mobility in organic material
- Organic degrades over time
  ➔New concept: All-semiconductor "hybrid" cell
  Gur et al., *Science* **310** (2005) 462.
- Low efficiencies under 1 Sun illumination.

Dye-sensitized cells

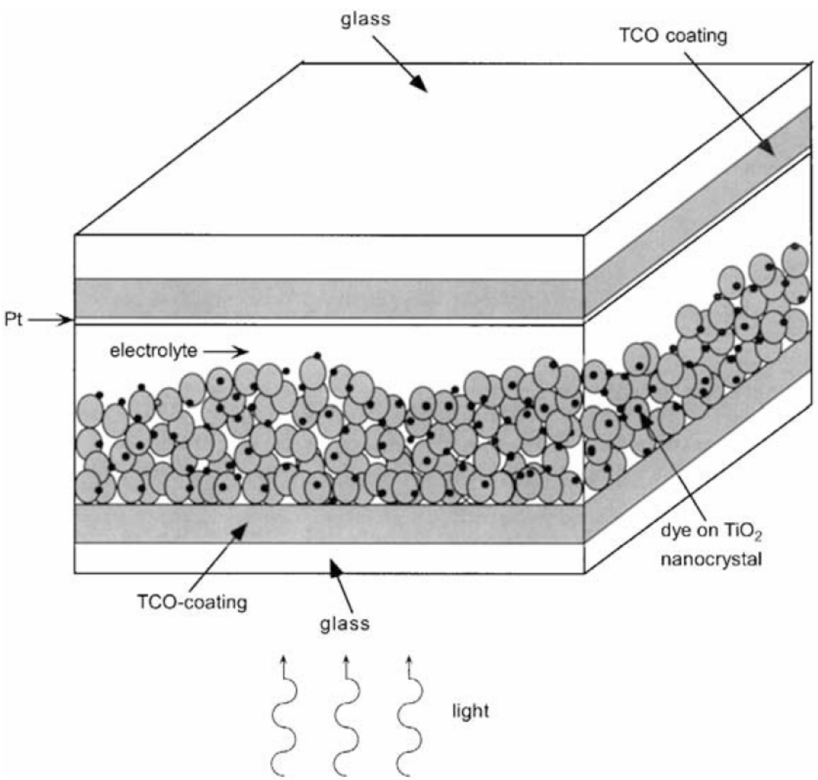


Fig. 9. Nanocrystalline TiO_2 dye-sensitised solar cell.

N. Lewis, *Science* **315** (2007) 798

Charge transfer events in die-sensitized solar cells

Image removed due to copyright restrictions. Please see Fig. 1 in: Moser, Jacques-E. "Solar Cells: Later Rather Than Sooner." *Nature Materials* 4 (October 2005): 723-724.

1. Absorption (Good)
2. Charge transfer (Good)

3, 5. Recombination (Bad)
4, 6. Redox (Good)

J.-E. Moser, *Nat. Mater.* **4** (2005) 723

Dye-sensitized cells

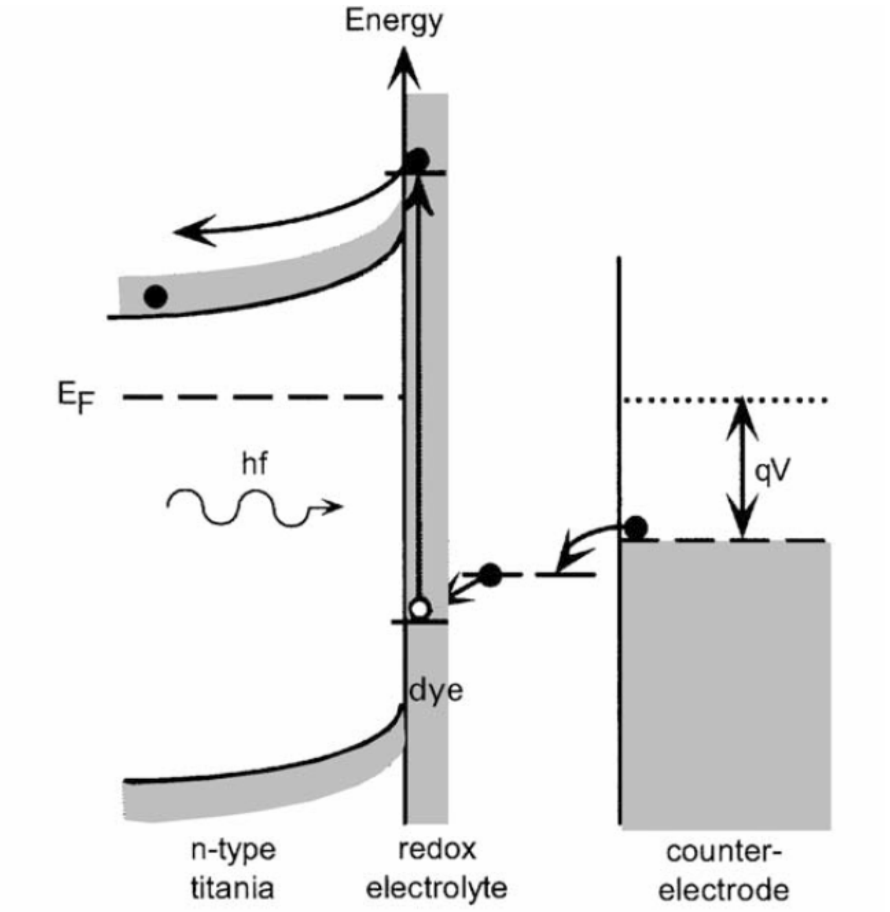


Fig. 10. Energy relationships in a nanocrystalline dye cell in region where the titania semiconductor is coated by the dye.