Consiglio Nazionale delle Ricerche
Istituto per la Sintesi Organica e la Fotoreattività (CNR-ISOF)
Bologna (Italy)

Plastic solar cells

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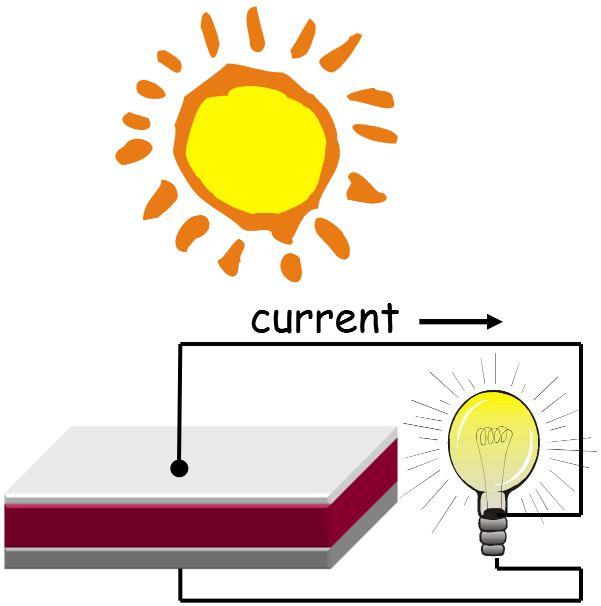
Outline

- Organic semiconductors
  - ✓ *Properties*
  - ✓ *Advantages and disadvantages*
- Plastic solar cells: some basics
  - ✓ *Generation of free carriers*
  - ✓ *Materials*
  - ✓ *The role of active layer morphology*
- Current research trends and perspectives
- Concluding remarks

From solar light to electricity: main steps



- Absorption of solar light
- Creation of free charge-carriers
- Transport of carriers to the contacts
- Extraction of carriers

ORGANIC MATERIALS

Fantastic plastic

Polymer materials could bring down the cost of electricity production using photovoltaic technology to below $1 per watt for the first time, and enable mass-market, portable applications for photovoltaic technology.

Russell Gaudiana* and Christoph Brabec†
Konarka Technologies, 100 Foot of John Street, Boott Mill South, 3rd Floor Lowell, Massachusetts 01852, USA
e-mail: *rgaudiana@konarka.com; †cbrabec@konarka.com

Much of the early work on photoactive materials for photovoltaics focused on crystalline silicon, which dominates the commercial solar-energy field today. Several other materials, such as amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), are also now in various stages of commercialization, and are known as thin-film technologies. The lower manufacturing costs and higher production throughput of these materials potentially translate into lower electricity costs. Current thin-film technologies are expected to bring costs reasonably close to $1 per watt of electricity produced at peak solar power.

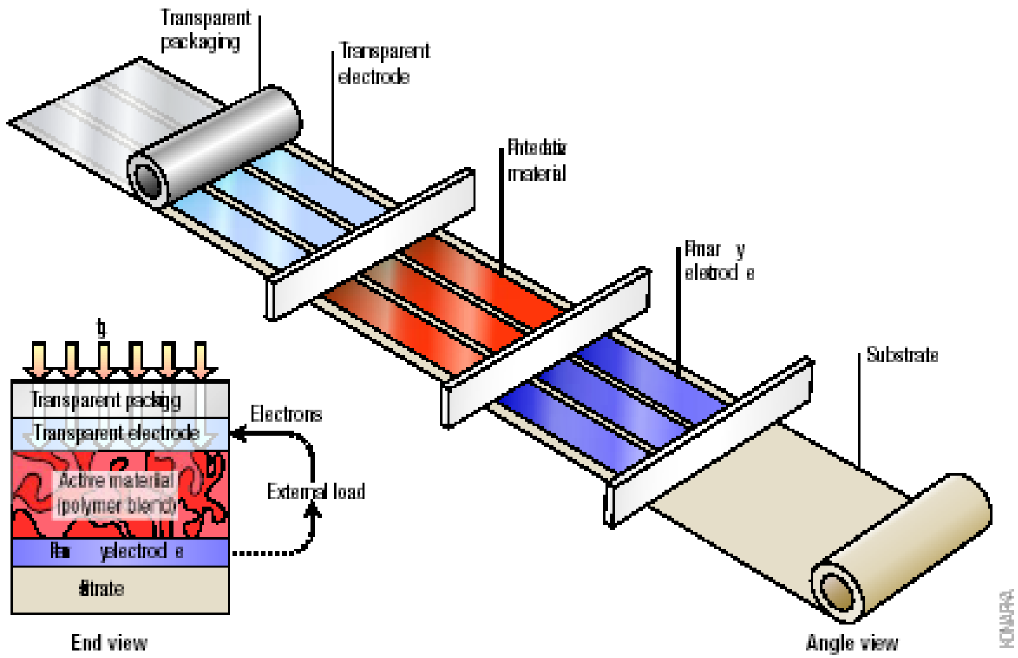
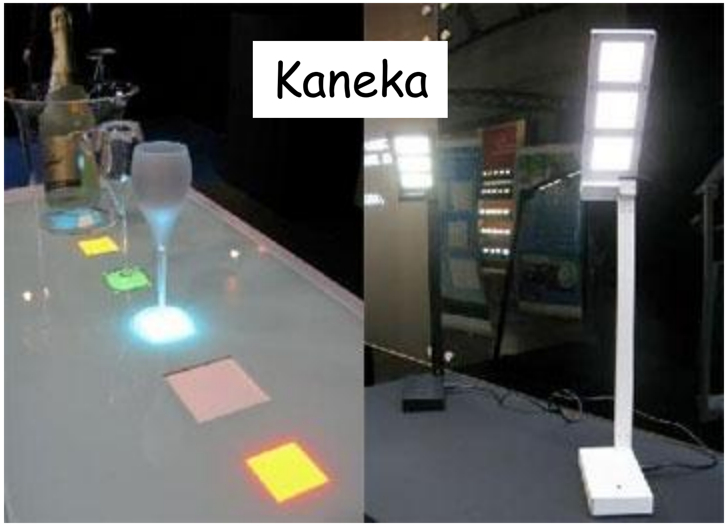


Figure 1 Polymer-based photovoltaic cells can be manufactured using standard printing processes.

Nature Photonics 2 (2008) 287

Plastic electronics is a reality



Advantages of organic semiconductors

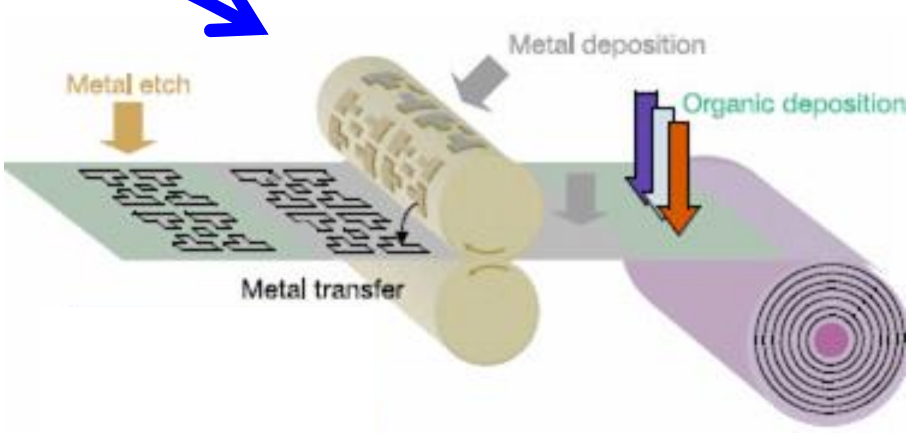
- Facile chemical tailoring of their properties
- High optical absorption coefficients
- Flexible or conformable devices can be fabricated
- Lightness in weight
- Low-cost thin-film technology

    No high temperature processes

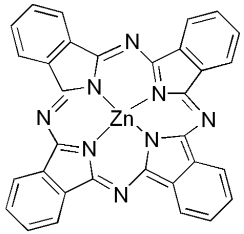
    Solution processable

    Roll-to-roll coating possible

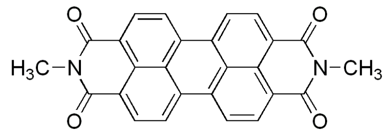
    Large-area device deposition



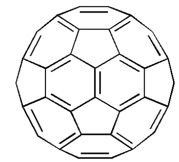
Polymers and low molecular weight molecules



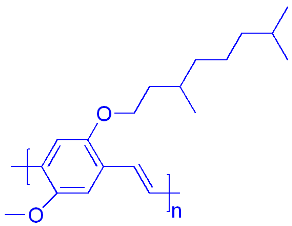
ZnPc



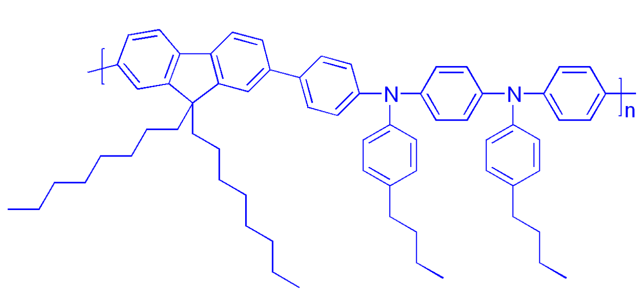
Me-Ptcdi



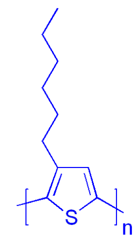
C_{60}



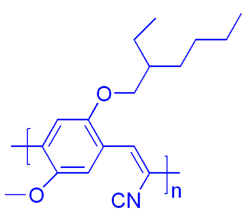
MDMO-PPV



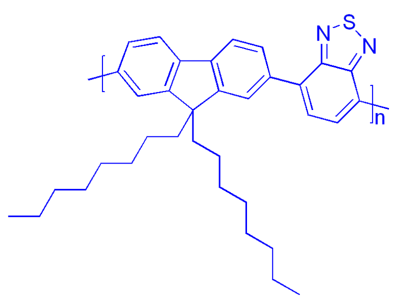
PFB



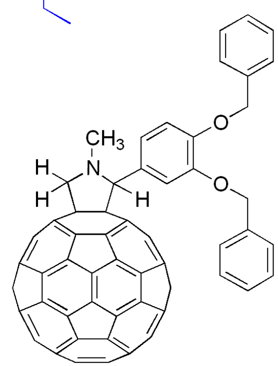
P3HT



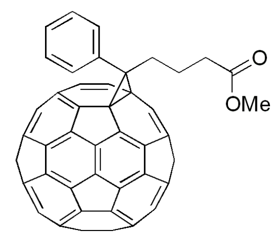
CN-MEH-PPV



F8BT



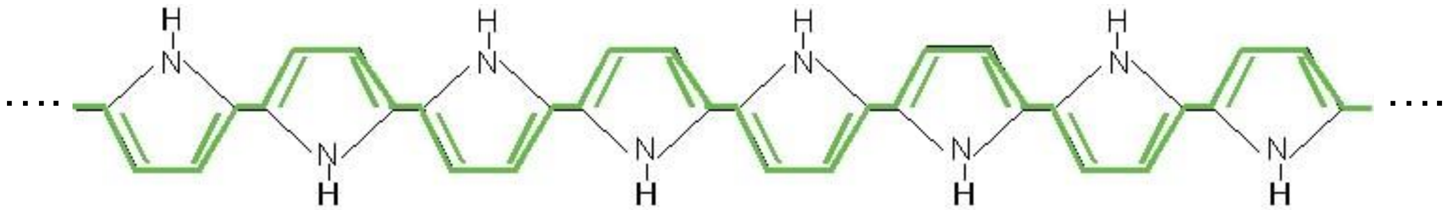
FPYE



PCBM

Organic semiconductors: conjugated molecular structures

➢ They have a molecular structure with a framework of alternating single and double chemical bonds (conjugation)

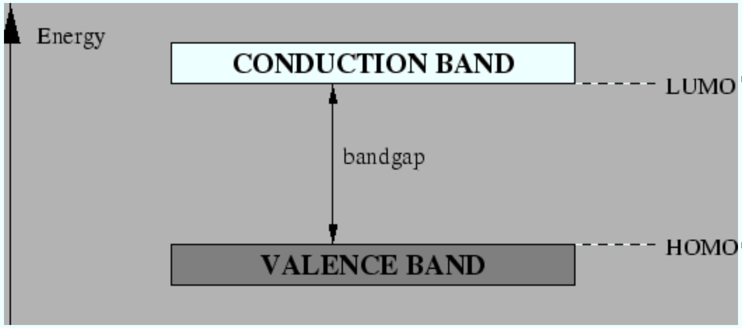


➢ They have intramolecular covalent bonds, but molecules are held together by weak intermolecular van der Waals interactions

Narrow electronic bandwidth formed in organic semiconductors

Disadvantages of organic semiconductors

Narrow electronic bandwith



Lowest **U**noccupied **M**olecular **O**rbital (**LUMO**)

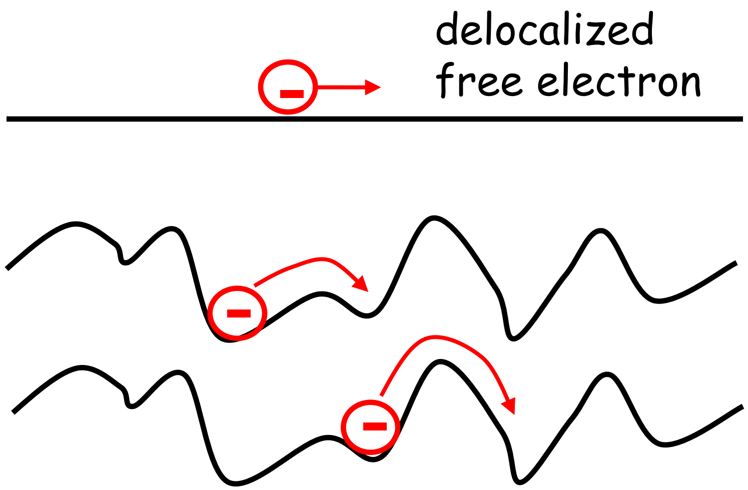
Highest **O**ccupied **M**olecular **O**rbital (**HOMO**)

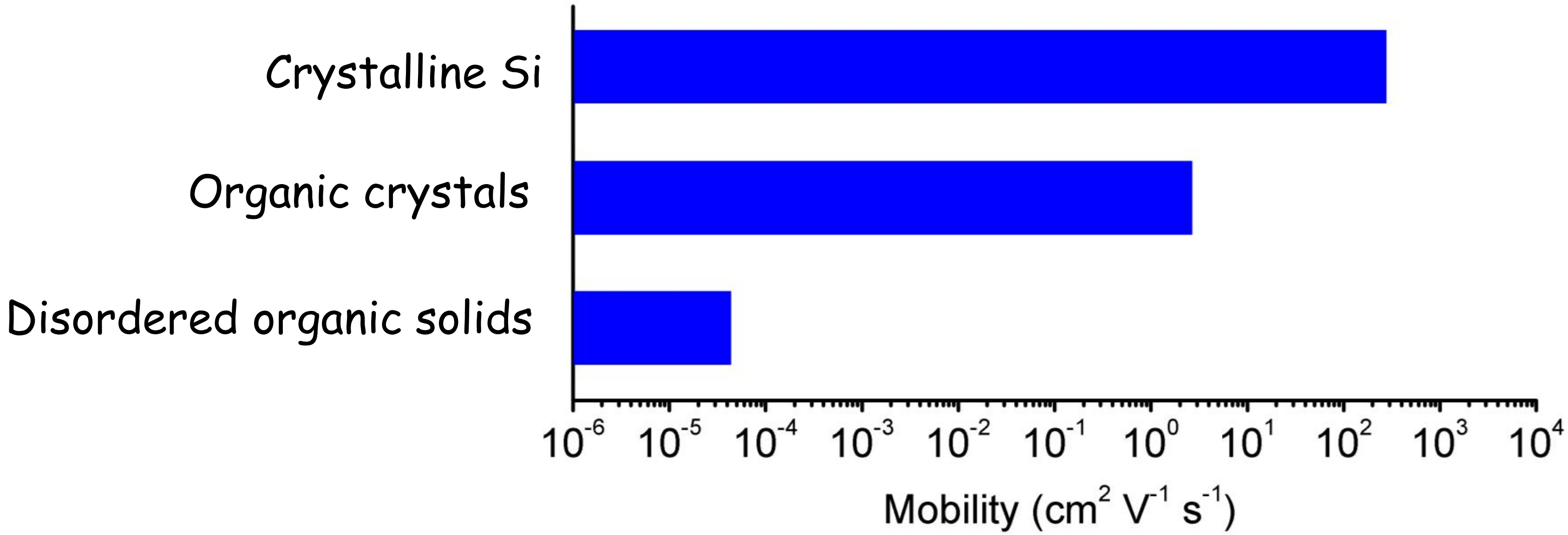
- Absorption spectrum narrower than in conventional inorganic semiconductors
- No band-like charge transport mechanism

Charge transport in organic semiconductors

No band-like transport mechanism but hopping transport between localized states

Low charge-carrier mobilities with respect to conventional inorganic semiconductors

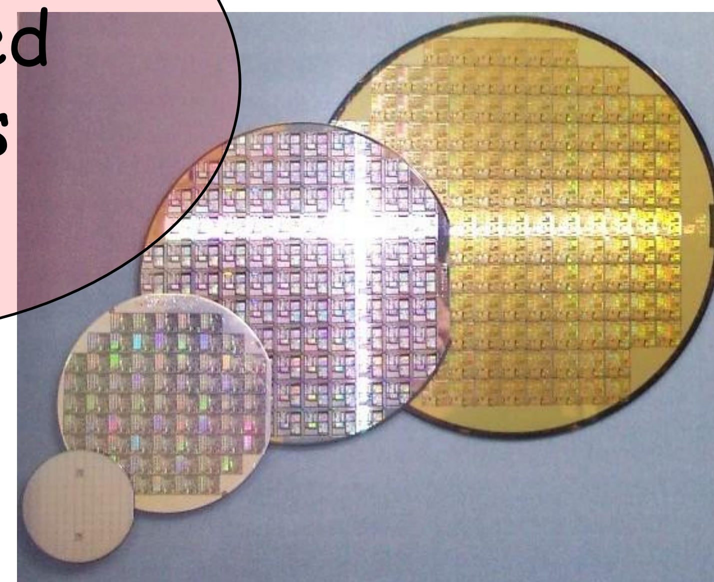




Conjugated polymers: plastic semiconductors

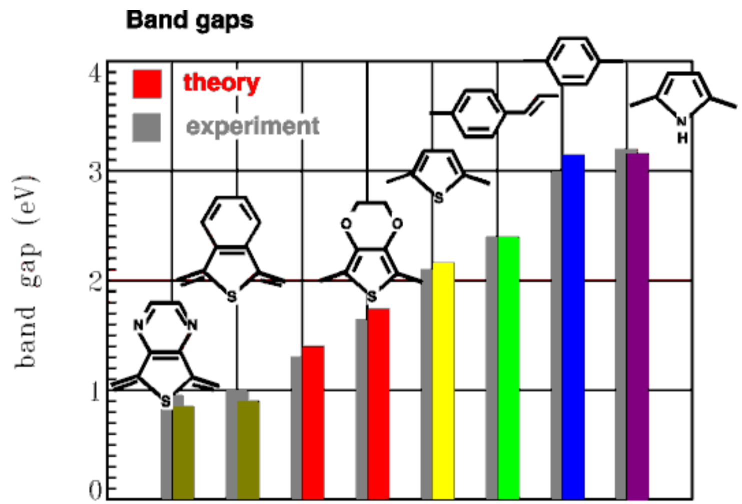
Mechanical properties of common plastics

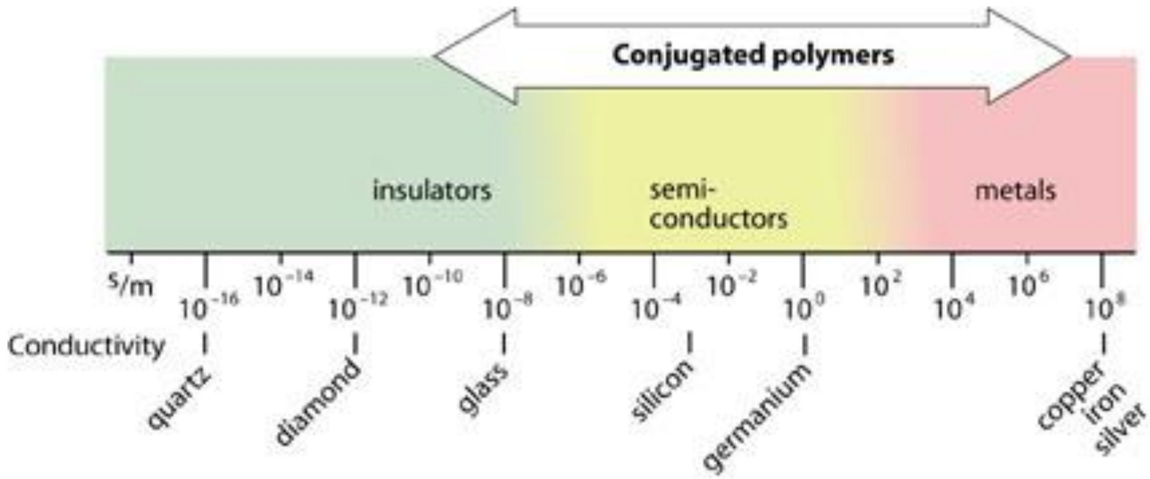
Conjugated polymers



Electronic properties similar to those of conventional semiconductors

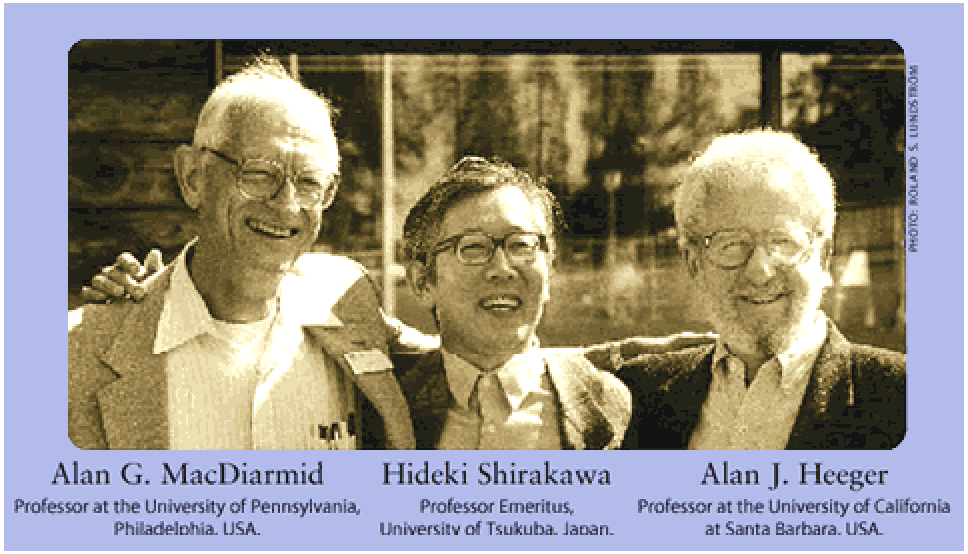
Conjugated polymers: tunability of their electronic properties





Nobel Prize for the discovery of conductive polymers

NOBEL 2000

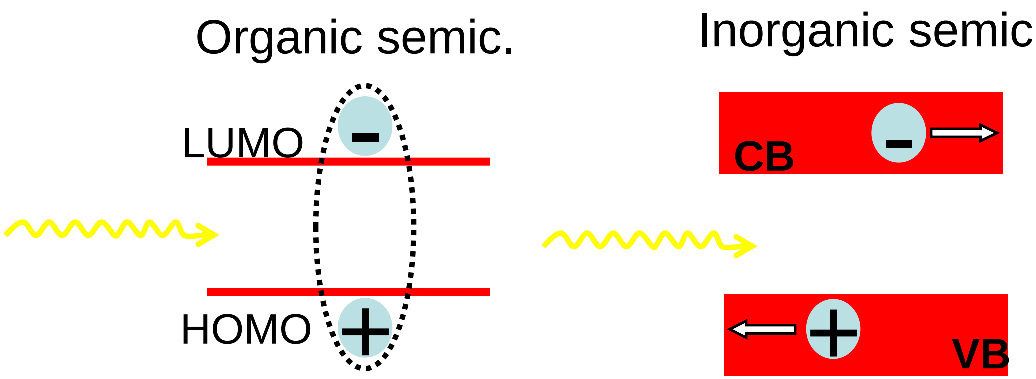


Alan J. Heeger, Alan G. MacDiarmid and Hideki Shirakawa have been awarded the Nobel Prize in Chemistry for showing how plastic can be made to conduct electric current. This surprising discovery has radically altered our view of plastic as a material. Conductive polymers today constitute a growing research field of great significance to chemists and physicists alike.

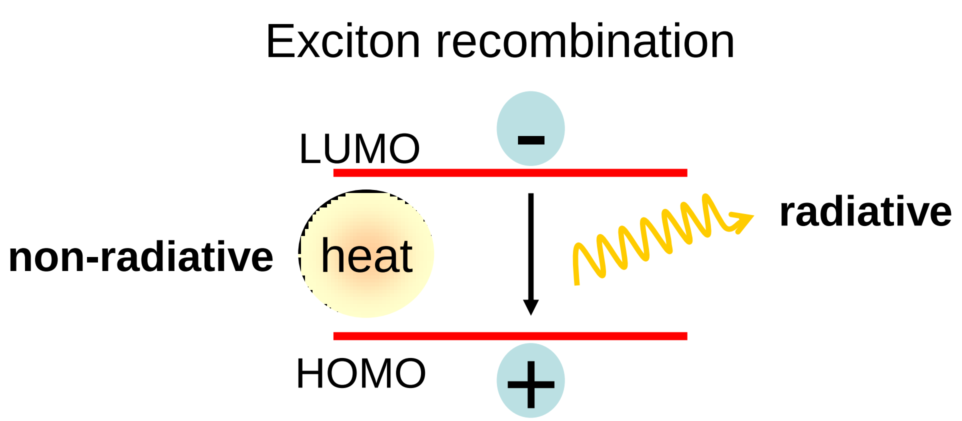
“Excitonic” character of organic semiconductors

Light absorption results in the formation of strongly bound electron-hole pairs (excitons) in organic materials, rather than free electron-hole pairs directly generated in inorganic semiconductors

To separate the bound electrons and holes, a driving force is required to overcome the exciton-binding energy (around 0.5 eV).

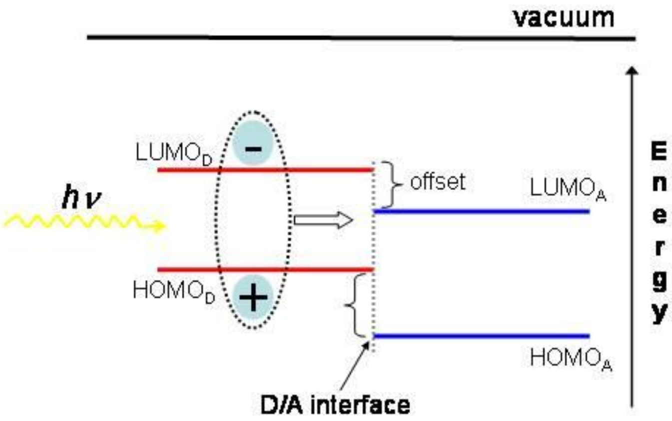


Excitons that are not split recombine, either radiatively or non-radiatively.

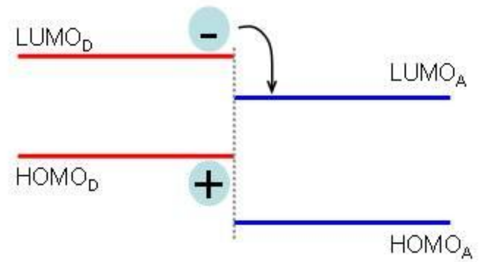


From excitons to free charge carriers: donor (D) and acceptor (A) materials

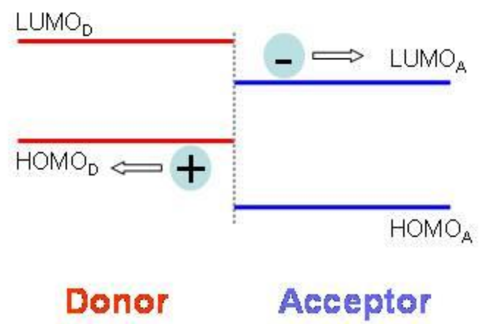
Excitons can be efficiently split at the interface between two materials with dissimilar energy levels: an electron-donor (D) and an electron-acceptor (A)



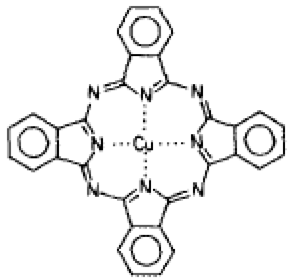
Excitons dissociate through a photoinduced charge transfer process



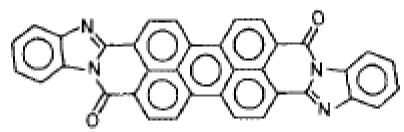
Upon charge transfer, electrons are transported in the electron-acceptor material and holes in the electron-donor material



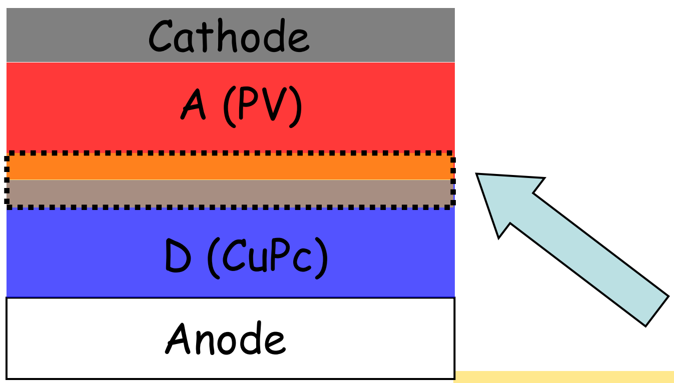
Tang's cell: the bilayer approach



CuPc



PV



limited photoactive region!

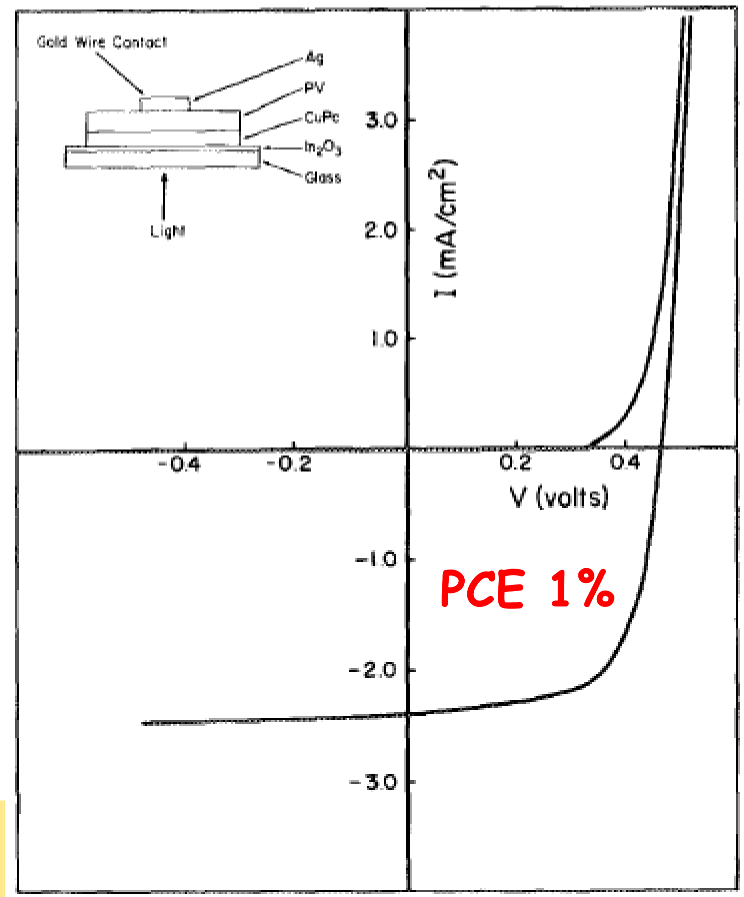
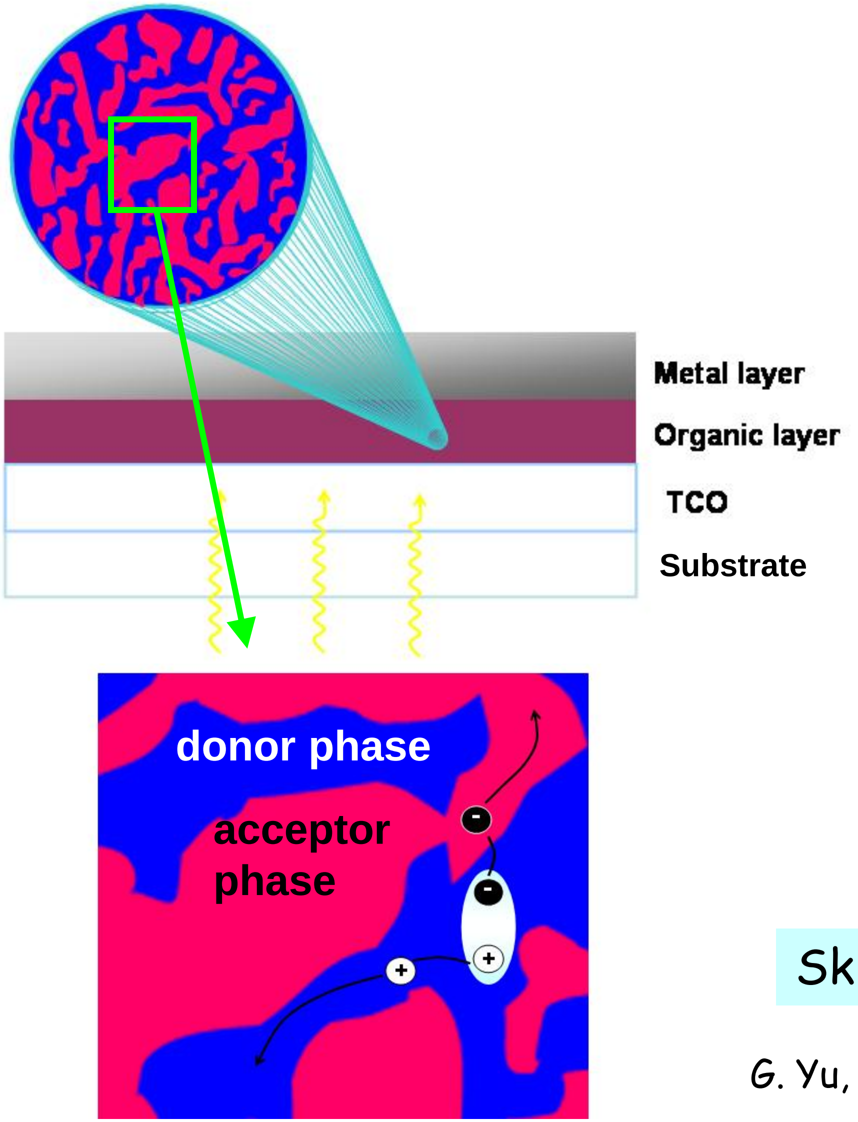


FIG. 1. Configuration and current-voltage characteristics of an ITO/CuPc (250 Å)/PV(450 Å)/Ag cell.

The photoactive region is limited by the exciton diffusion length (10-20 nm)

C.W. Tang, *Appl. Phys. Lett. 48* (1986) 184

The bulk-heterojunction (BHJ) approach



- ❑ Donor and acceptor materials are mixed together on the nanoscale level. Both materials must be very soluble in the same solvent!

- ❑ All photogenerated excitons are within a diffusion length (10-20 nm) of a D/A interface

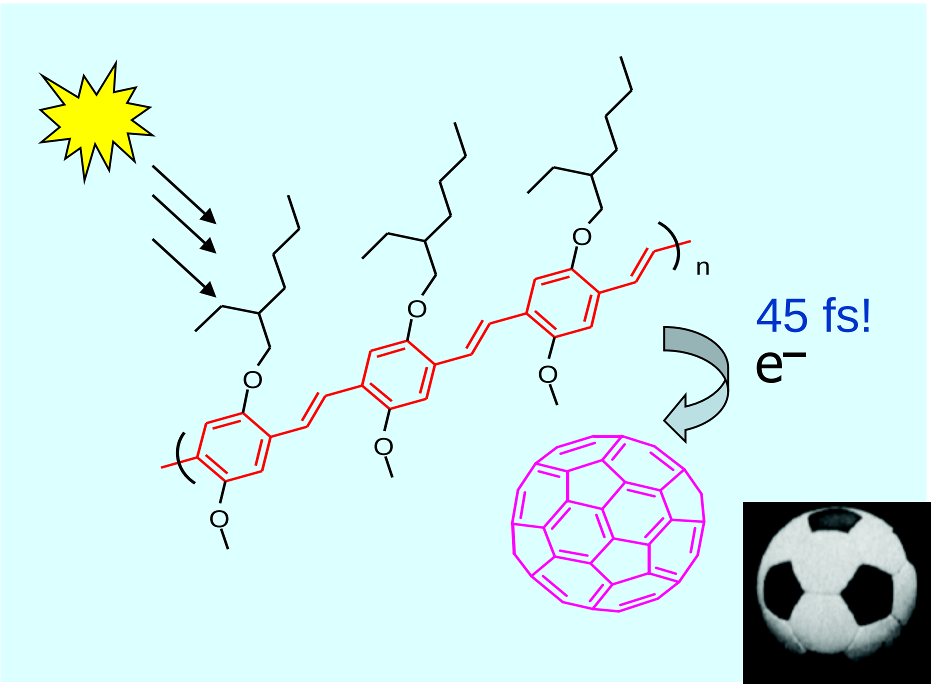
- ❑ Distributed active interfaces throughout the bulk of the device

- ❑ Percolation limit for both materials has to be reached. The blend morphology has to enable charge-carrier transport in the two different phases in order to minimize recombination

Skill lies in controlling the nanomorphology!

G. Yu, et al., *Science* *270*, (1995) 1789

Conjugated polymers – Fullerene (C_{60}): excellent D-A pairs



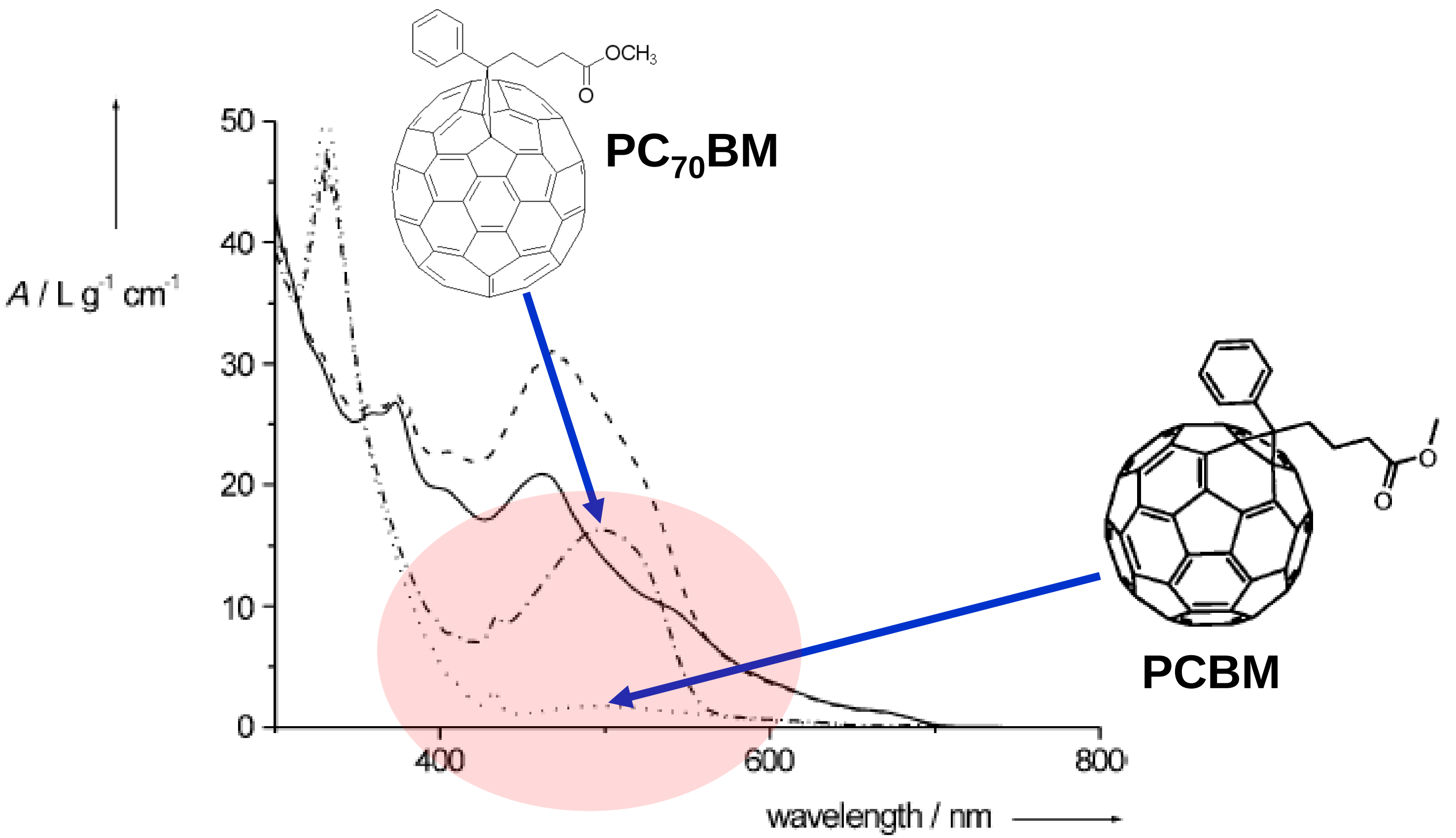
A number of conjugated polymer-fullerene pairs exhibit ultrafast photoinduced charge transfer (45 fs) with a back transfer of orders of magnitude slower

Every photon absorbed yields one pair of separated charges!

Quantum efficiency for charge separation approaches unity

N.S. Sariciftci et al., *Science* *258* (1992) 1474

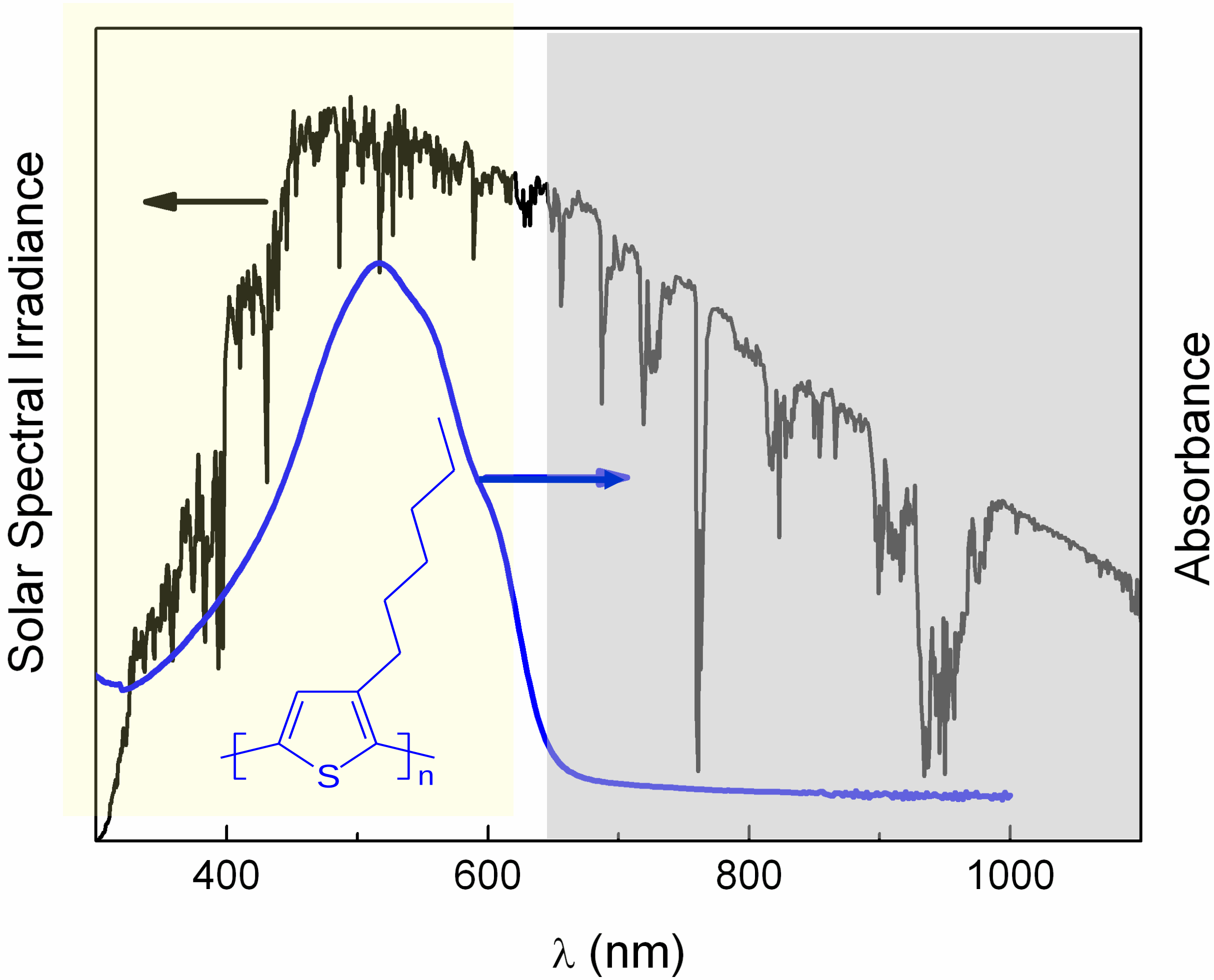
Common soluble derivatives of fullerenes



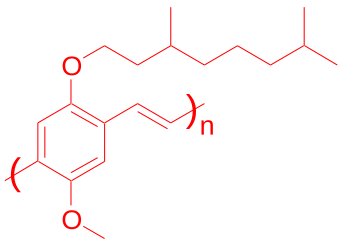
In polymer/fullerene BHJ solar cells, the donor polymer is also the main light absorber component

M.M. Wienk et al., *Angew. Chem. Int. Ed. 42* (2003) 3371

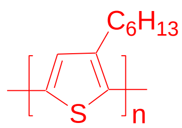
Narrow electronic bandwidth, narrow absorption bands



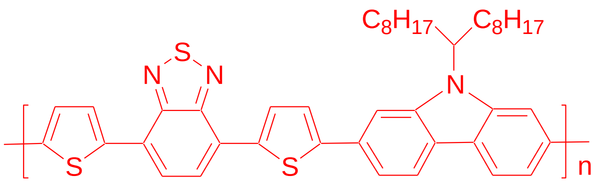
Common donor and acceptor materials



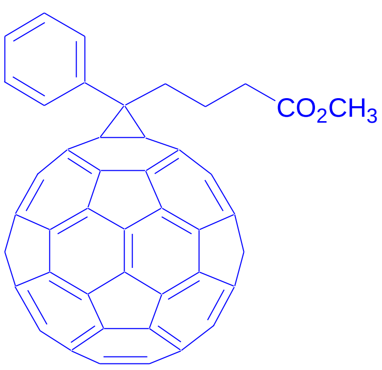
MDMO-PPV



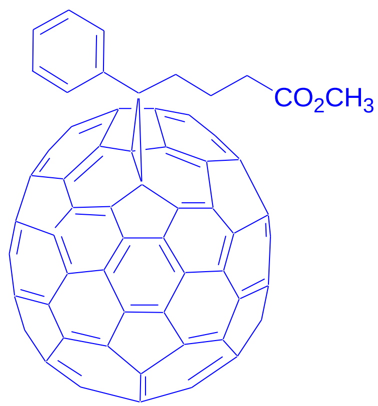
P3HT



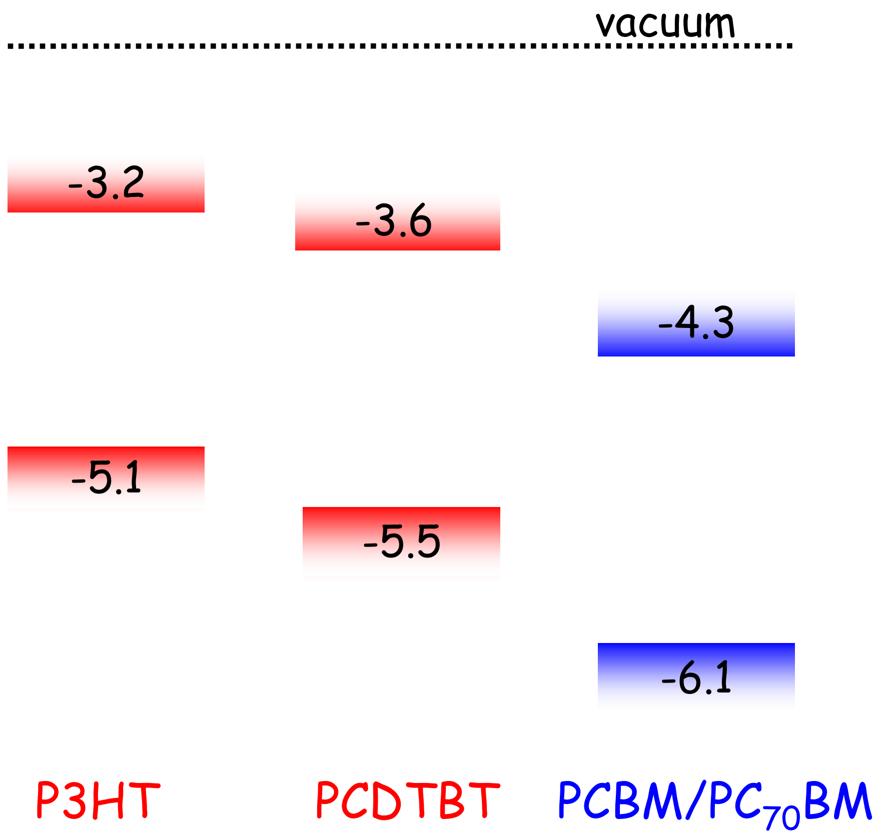
PCDTBT



PCBM

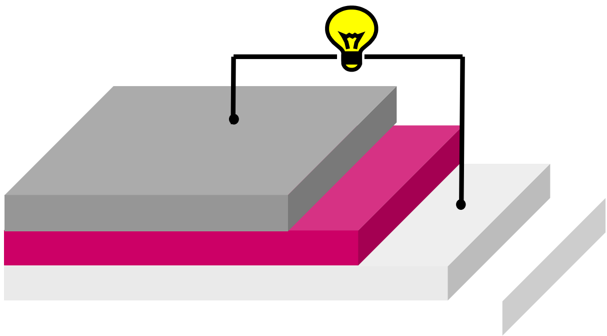


$PC_{70}BM$

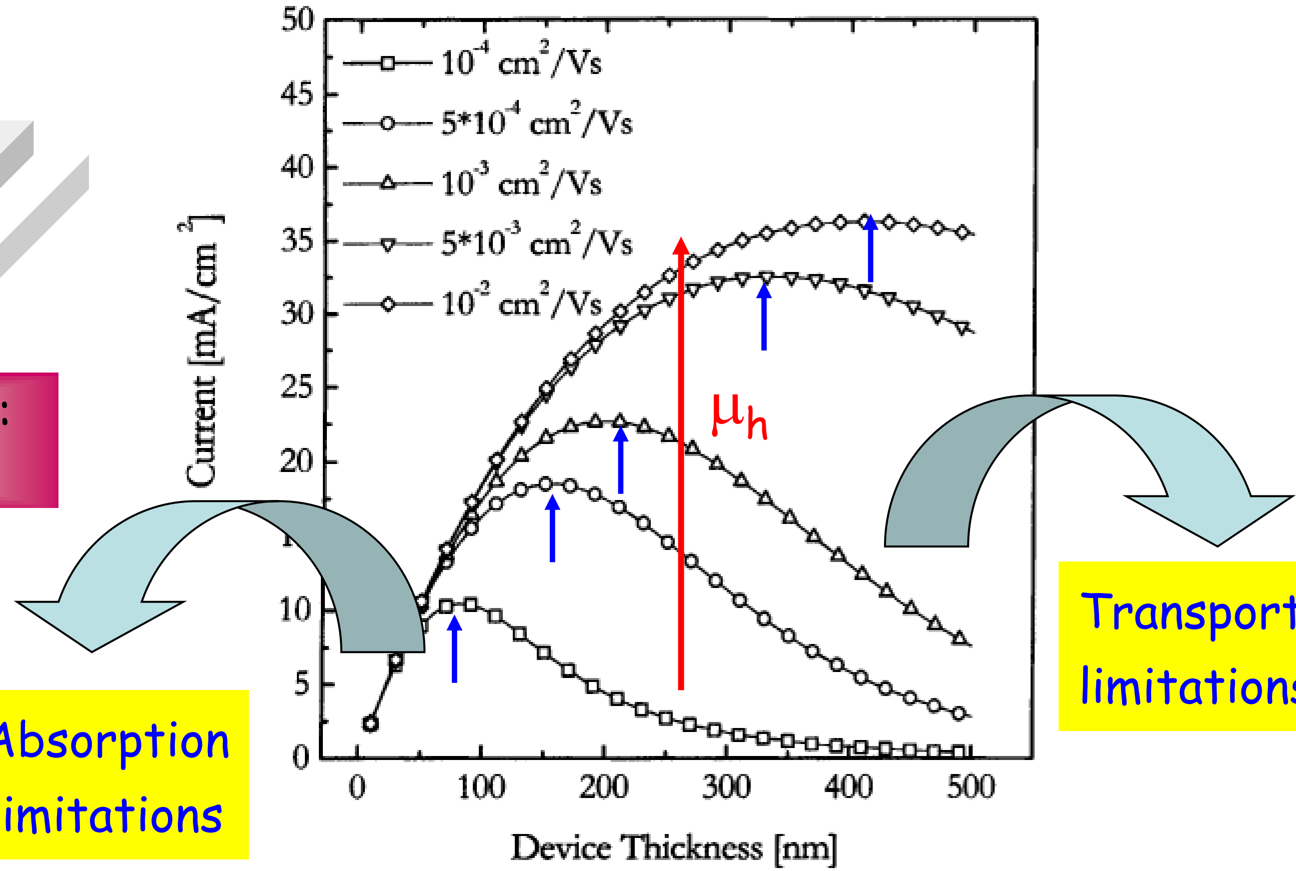


Ultra-thin film photovoltaic technology

Polymer:PCBM BHJ solar cells

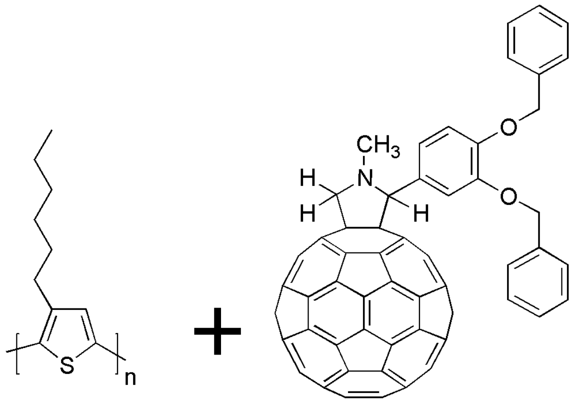


Active layer thickness:
100-300 nm

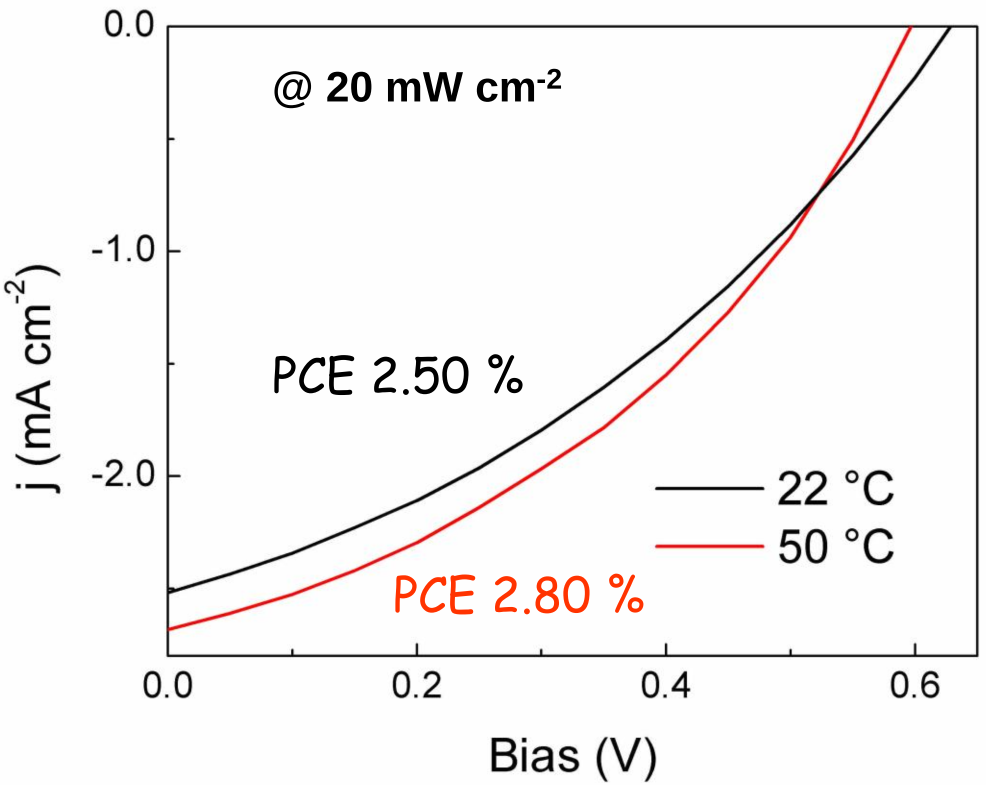


C.J. Brabec et al. *Synth. Metals 121* (2001) 1517

Positive temperature dependence of efficiency



P3HT + FPYE

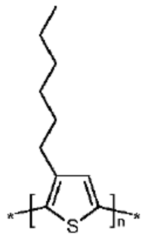


A consequence of the (poor) charge transport mechanism!

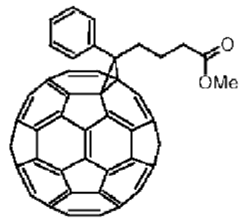
N. Camaioni et al., *Adv. Mater., 14*, (2002) 1735

E.A. Katz et al., *J. Appl. Phys., 90* (2001) 5343

The crucial role of blend morphology

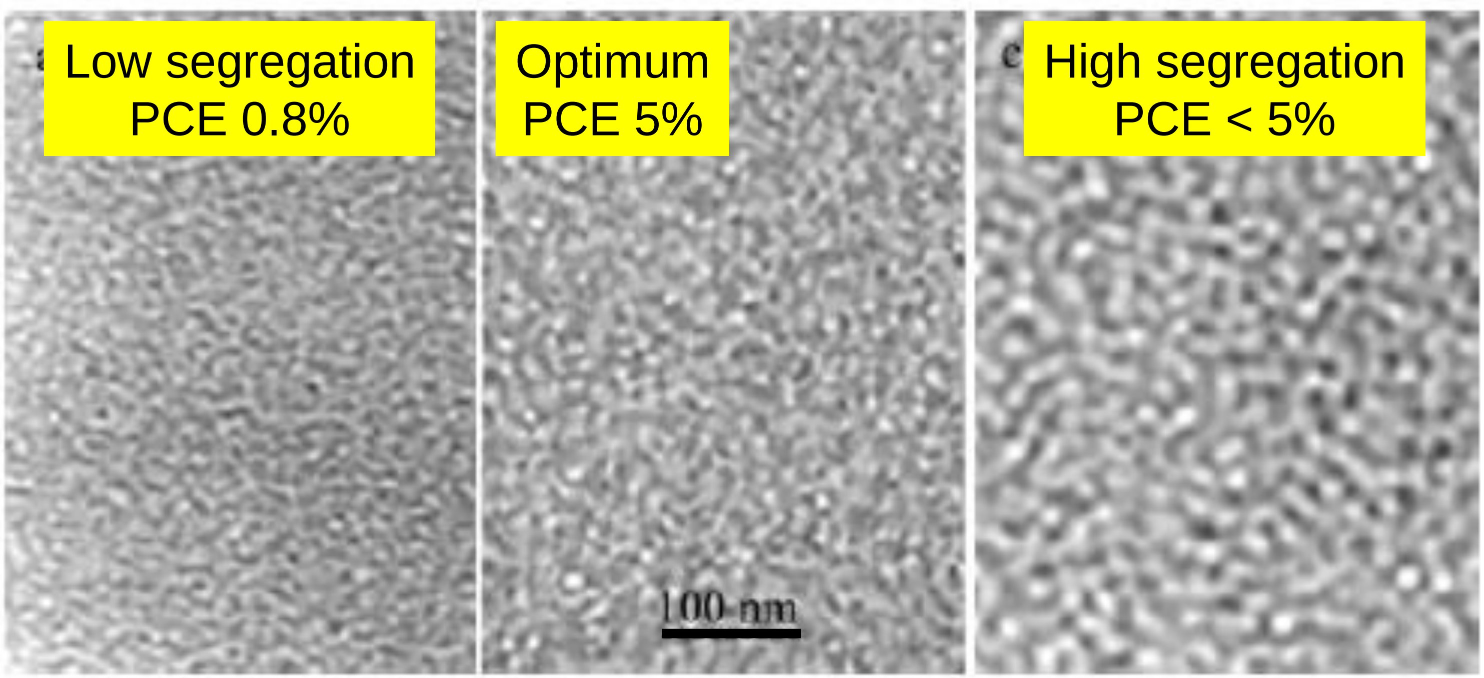


P3HT



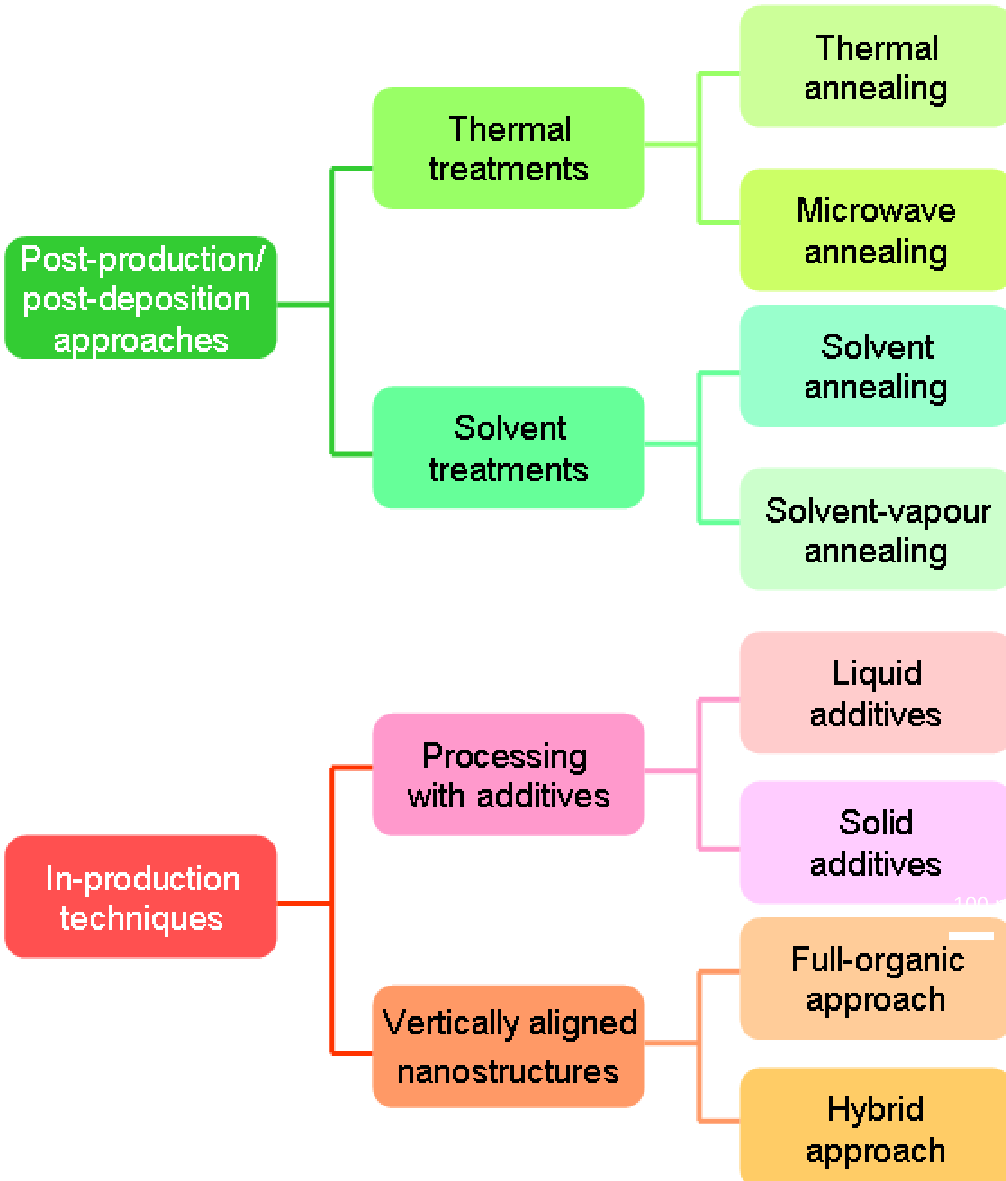
PCBM

P3HT:PCBM (1.0:0.8 by wt)



W. Ma et al., *Adv. Funct. Mater. 15* (2005) 1617

Protocols for the optimization of active layer properties



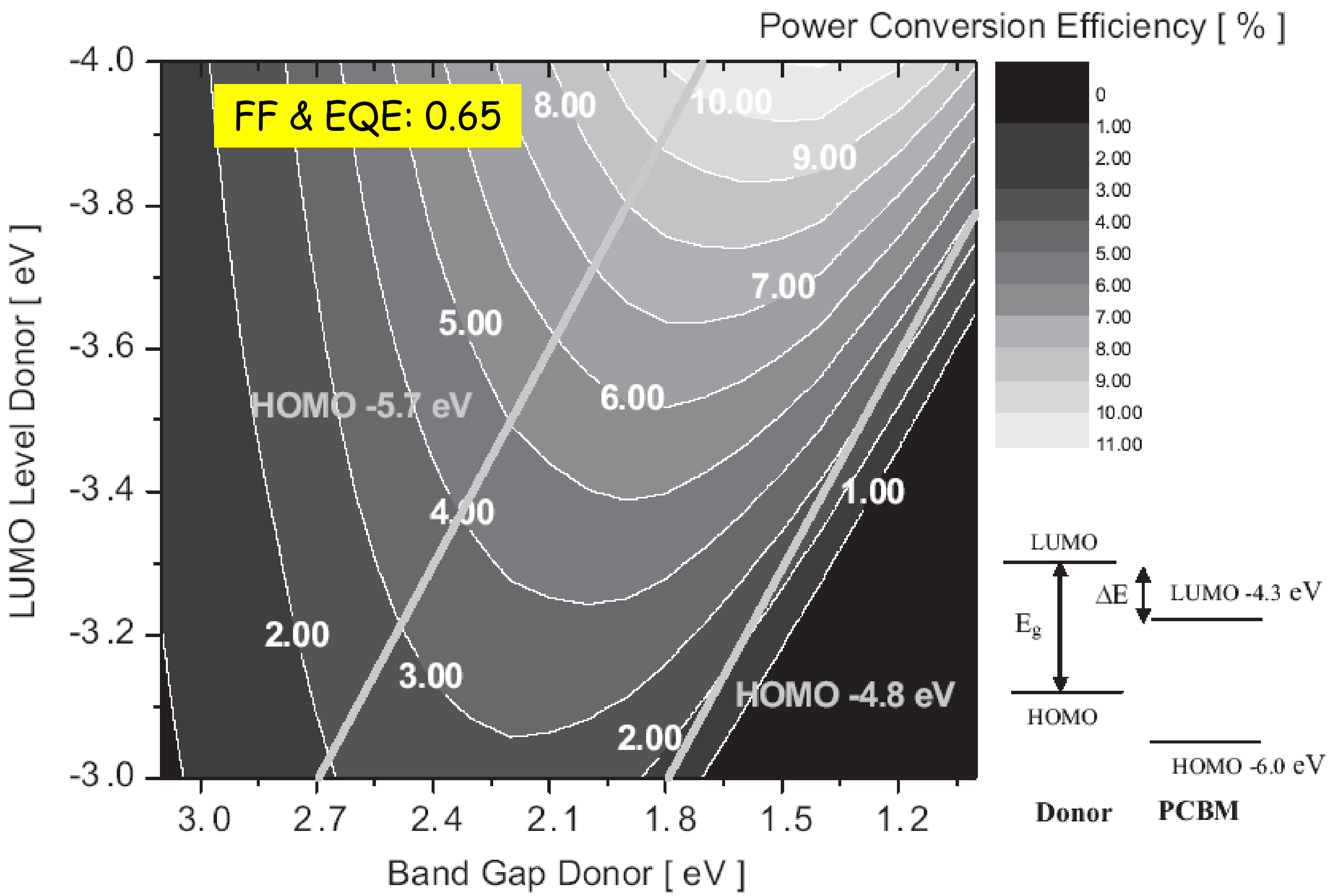
N. Camaioni, et al., *J. Mater. Chem.*, *12*, (2002) 2065
N. Camaioni, et al., *Adv. Mater.*, *14*, (2002) 1735
W. Ma et al., *Adv. Funct. Mater. 15* (2005) 1617

G. Li et al., *Nature Mater. 4*, (2005) 864

J. Peet et al., *Nature Mater. 6*, (2007) 497

These protocols often induce also an improvement of the optical and transport properties of the active layer

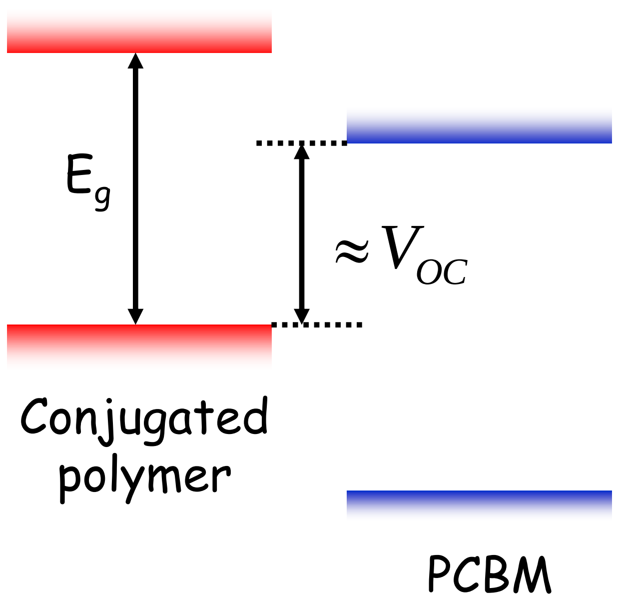
Perspectives



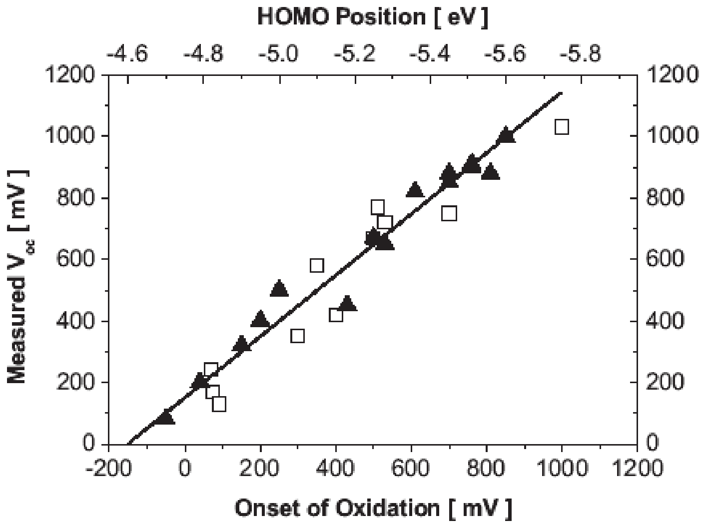
Adv. Mater. 18 (2006) 789

Conjugated polymers with optimised energy levels are required

Current direction: development of polymers with optimised energy levels



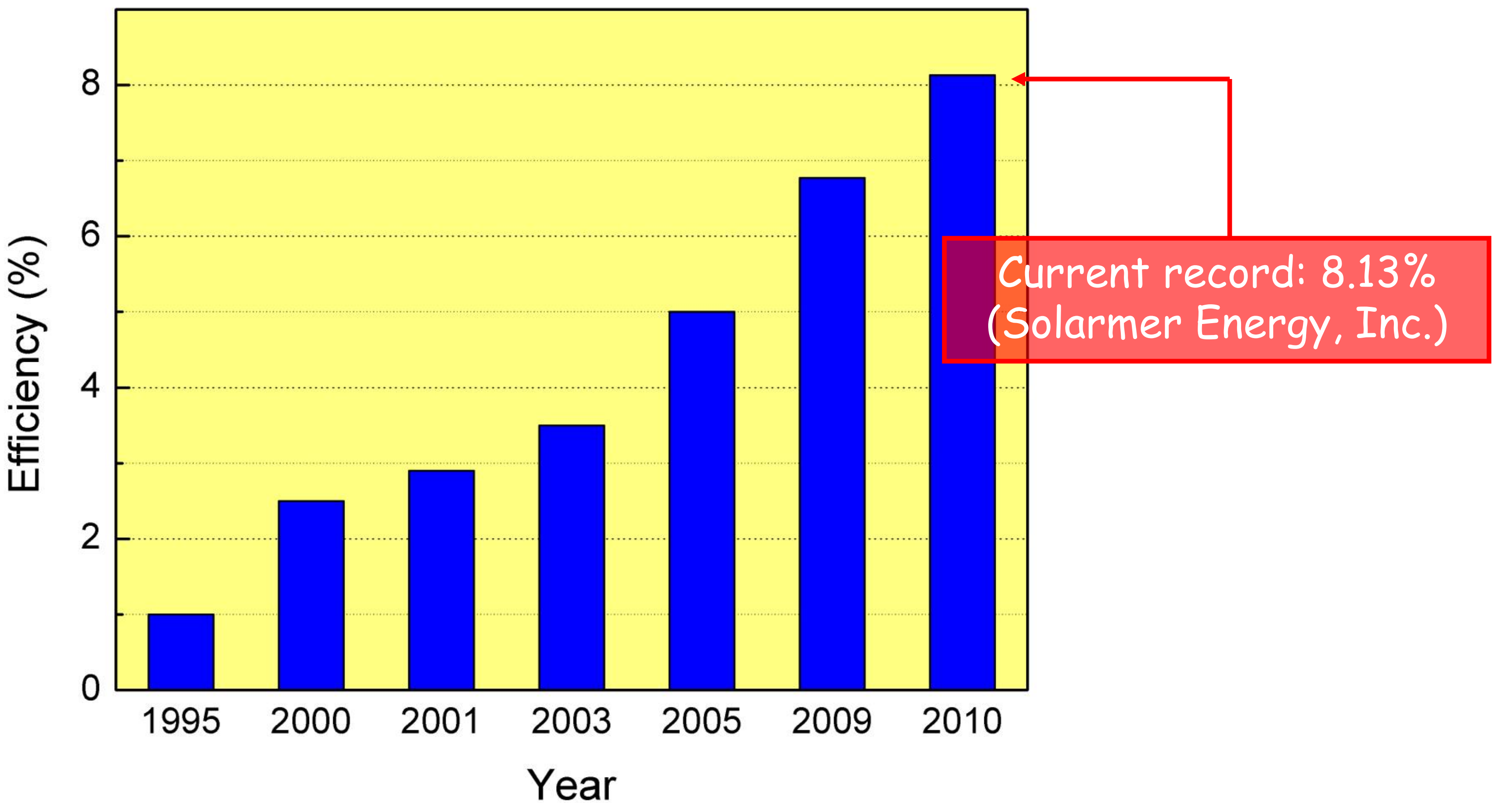
$$V_{OC} \approx \frac{1}{e}\left(HOMO_{Polymer} - LUMO_{PCBM}\right)$$



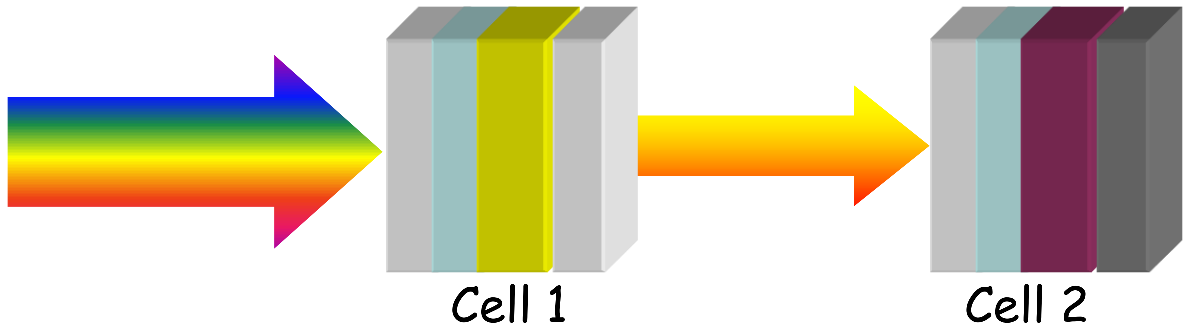
M.C. Scharber et al., *Adv. Mater. 18* (2006) 789

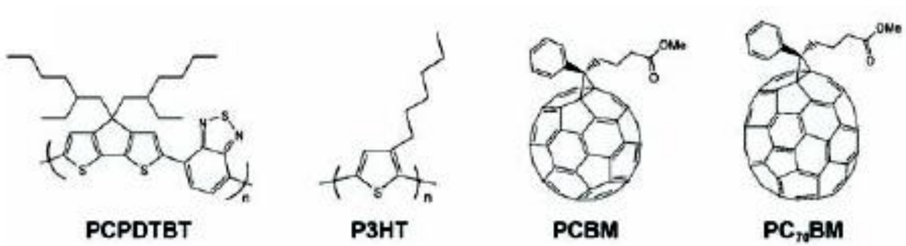
- Polymers with a low energy gap (E_g < 2 eV) for higher short circuit current
- Polymers with a deep HOMO level for higher open circuit voltage
- High hole mobility

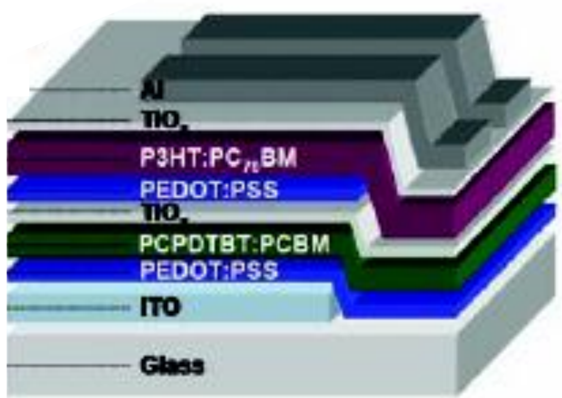
Efficiency evolution and state of the art

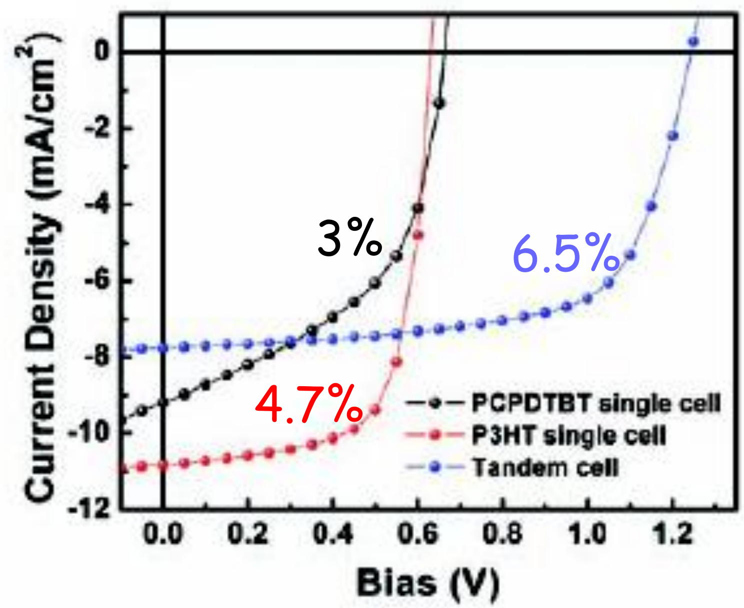


Plastic tandem solar cells



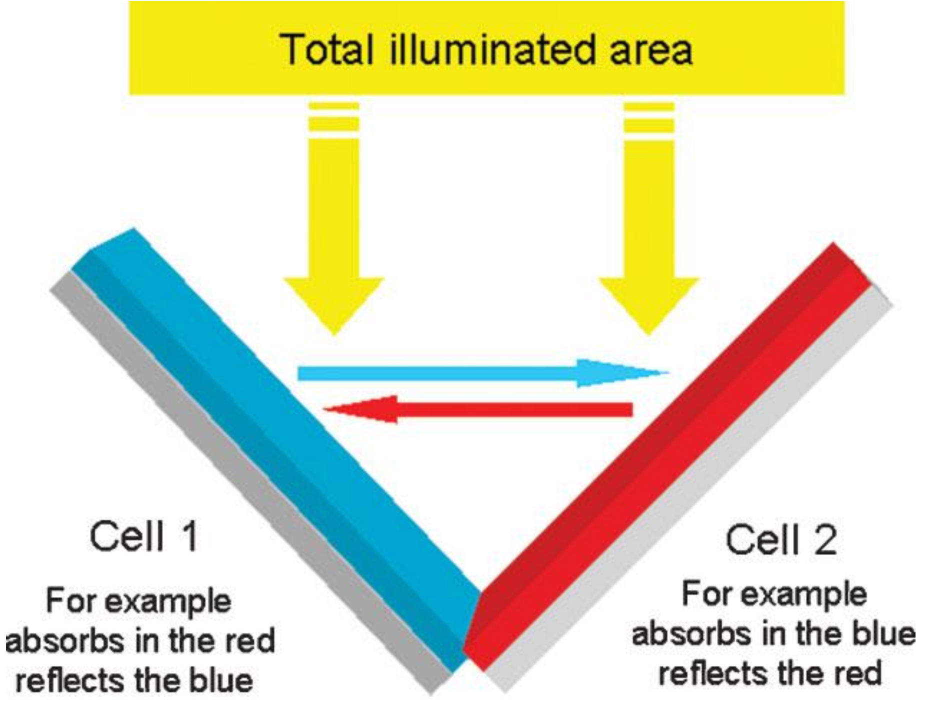






Kim et al., *Science 317* (2007) 222

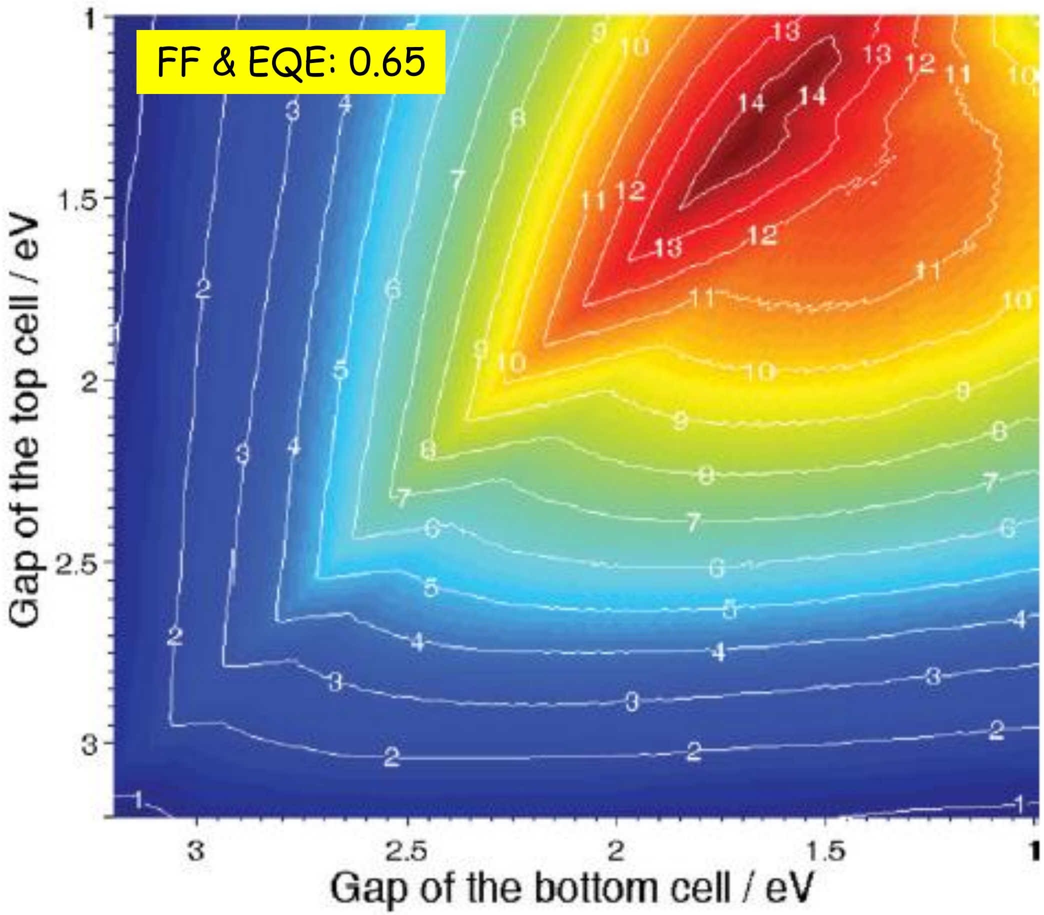
Folded solar cells



www.ifm.liu.se/biorgel/Research_OptoElectronics.html

K. Tvingstedt et al., *Appl. Phys. Lett.* 2007, 91, 123514

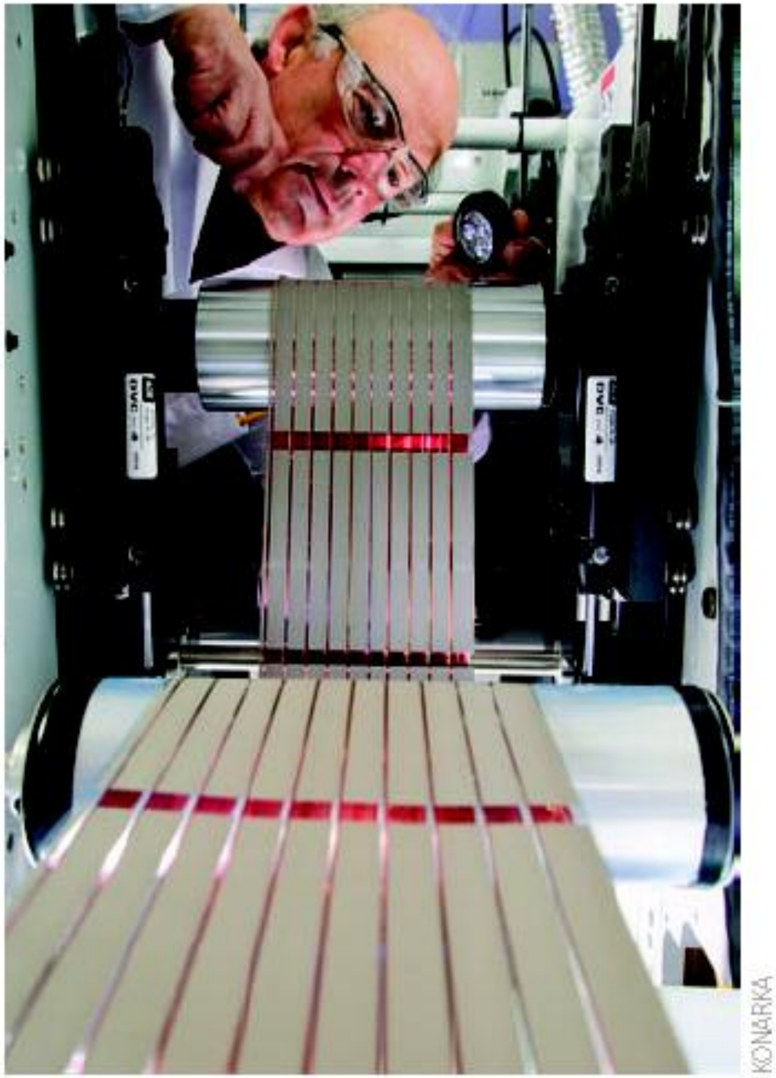
Perspectives for tandem plastic solar cells



PCE up to 15%

Adv. Mater. 20 (2008) 579

Roll-to-roll production of plastic PV modules



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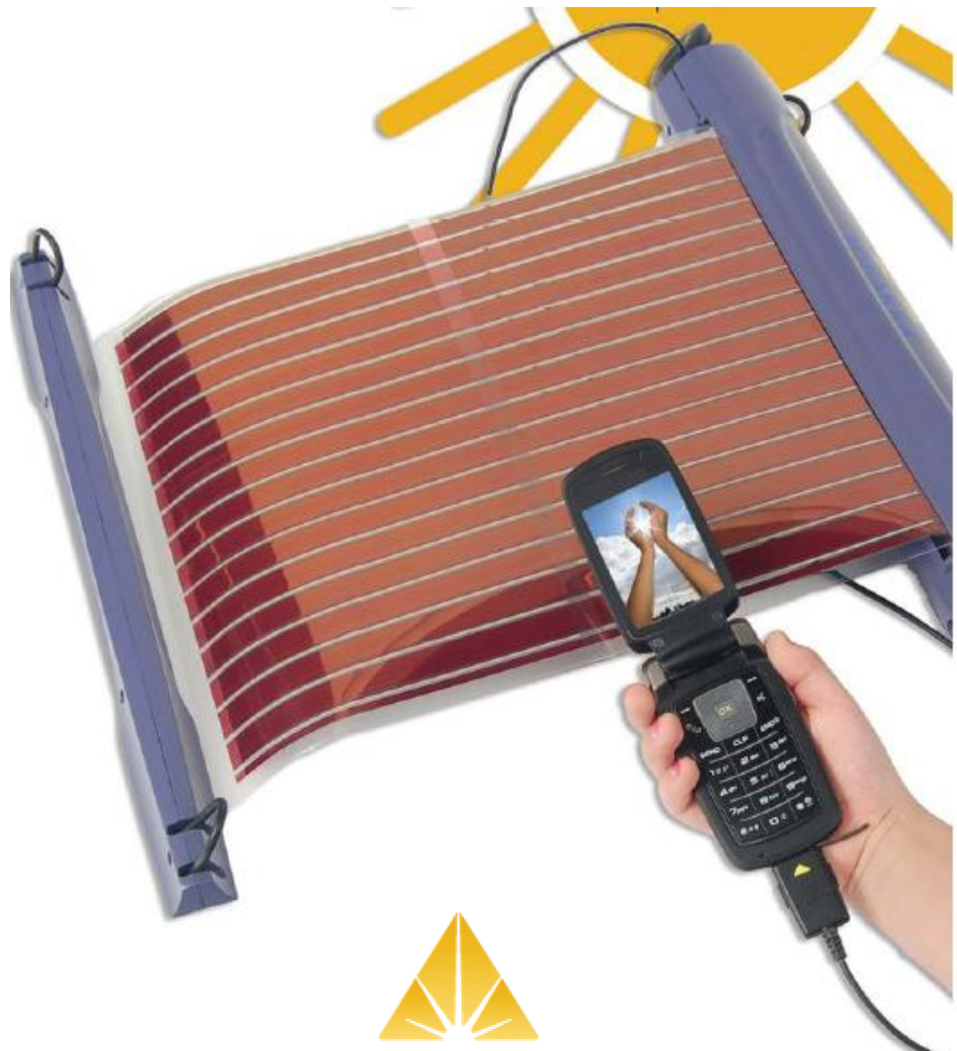
Plastic photovoltaic modules

Applications



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Applications

Applications

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Applications

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Concluding remarks

- Semitransparent, lightweight, flexible printable photovoltaic modules can be produced (are produced)

- The colour of the modules can be tuned

- The performance of plastic solar cells are steeply increasing

- Efficiency up to 15% have been predicted for tandem structures

- Chemistry will have a great role in the development of innovative smart materials

Thank you for your attention!