Outline

6.8 Organic and Perovskite Solar Cells

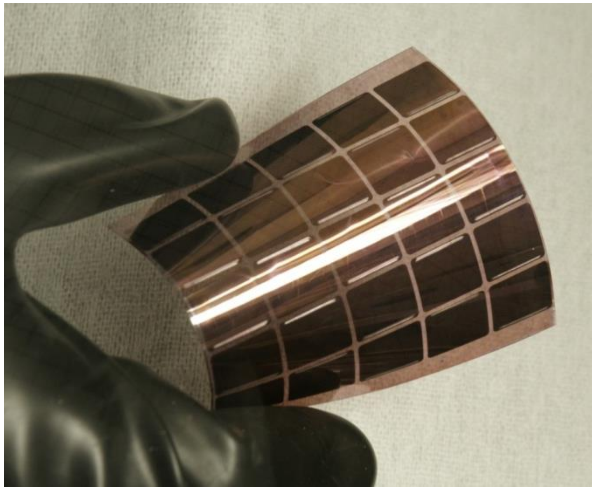
6.8.1 Organic Semiconductors

6.8.2 Low Bandgap Materials

6.8.3 Semitransparent and Tandem Solar Cells

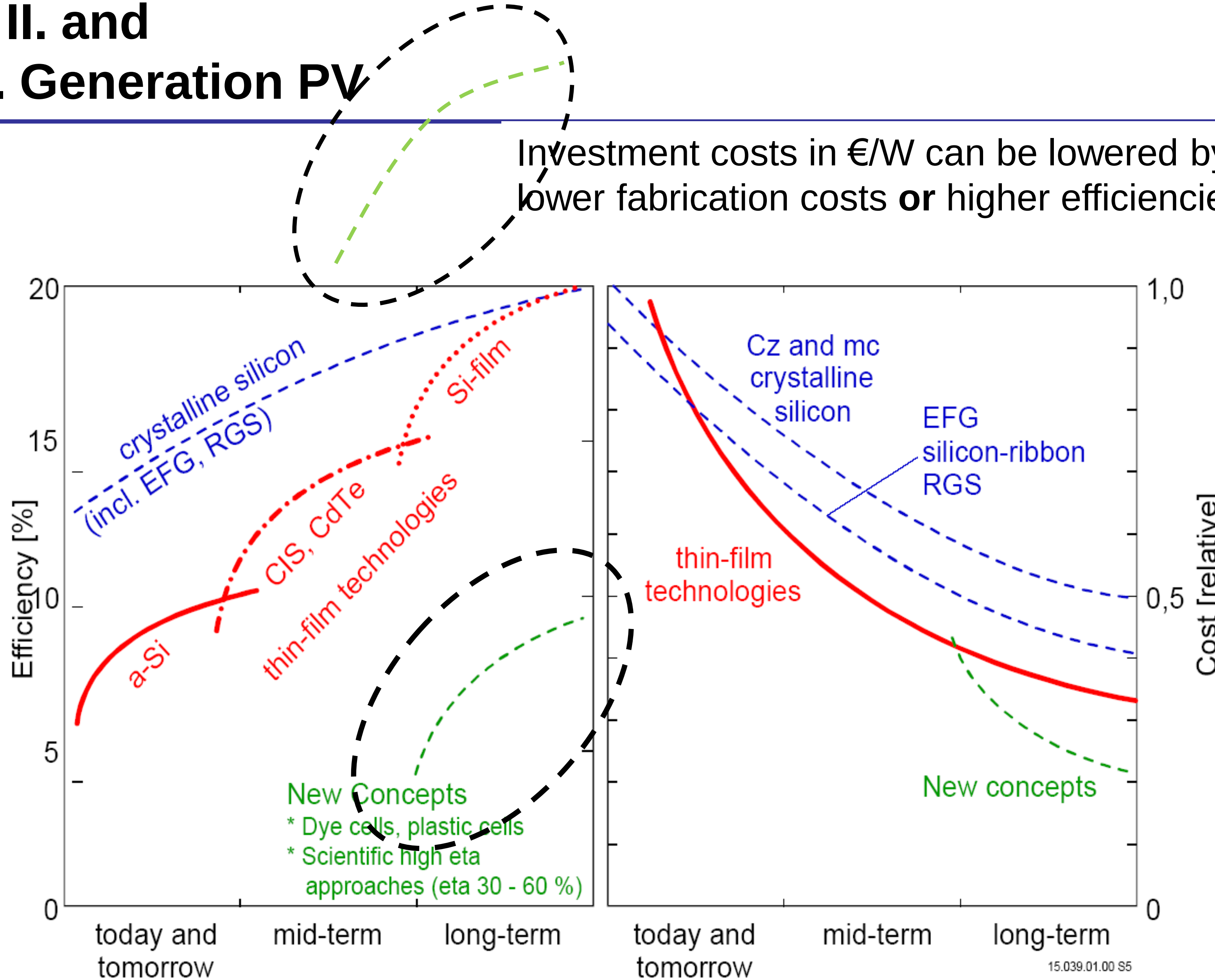
6.8.4 OPV Industry

6.8.5 Perovskite Solar Cells

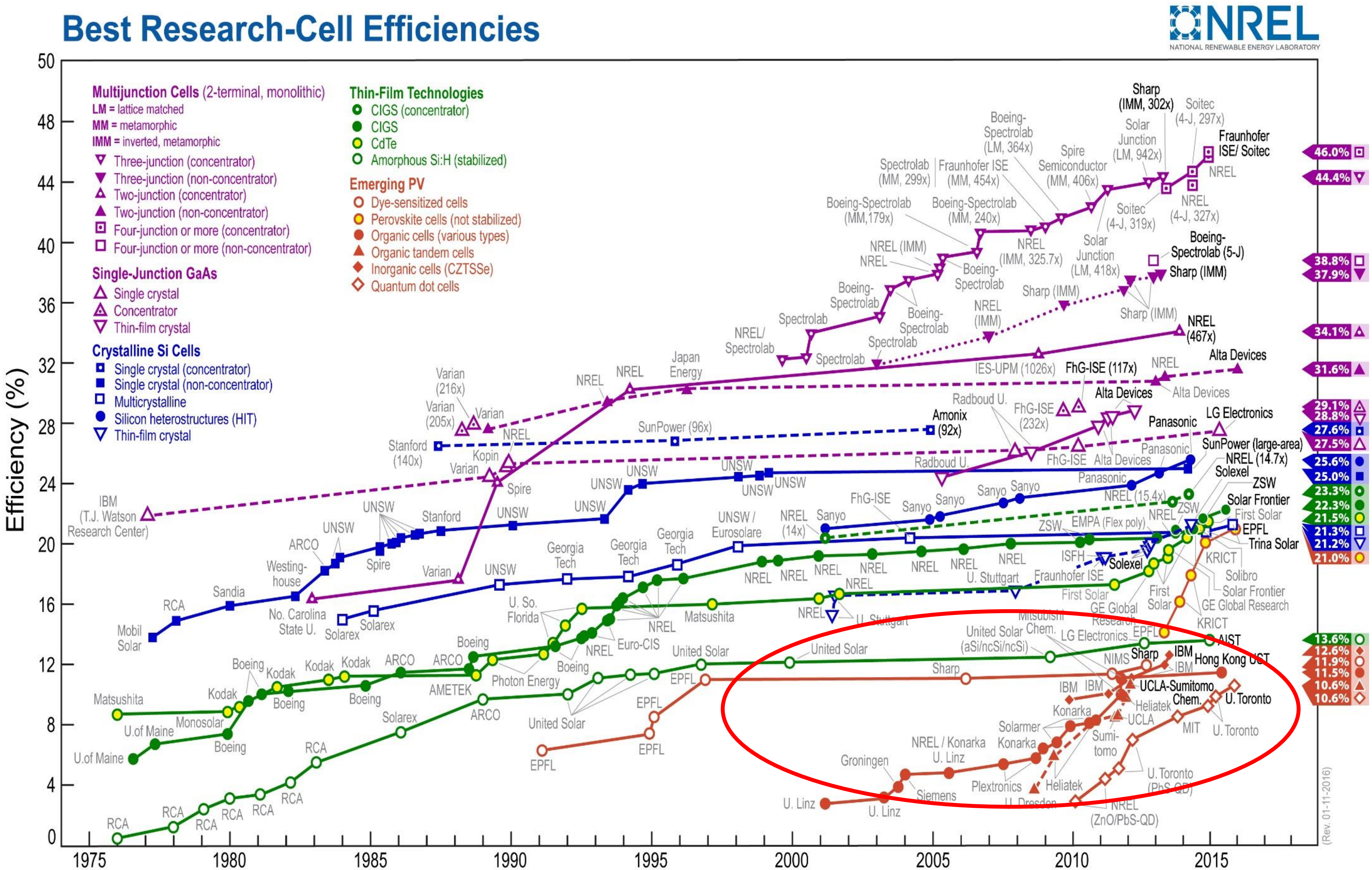


I., II. and
III. Generation PV

Investment costs in €/W can be lowered by lower fabrication costs **or** higher efficiencies

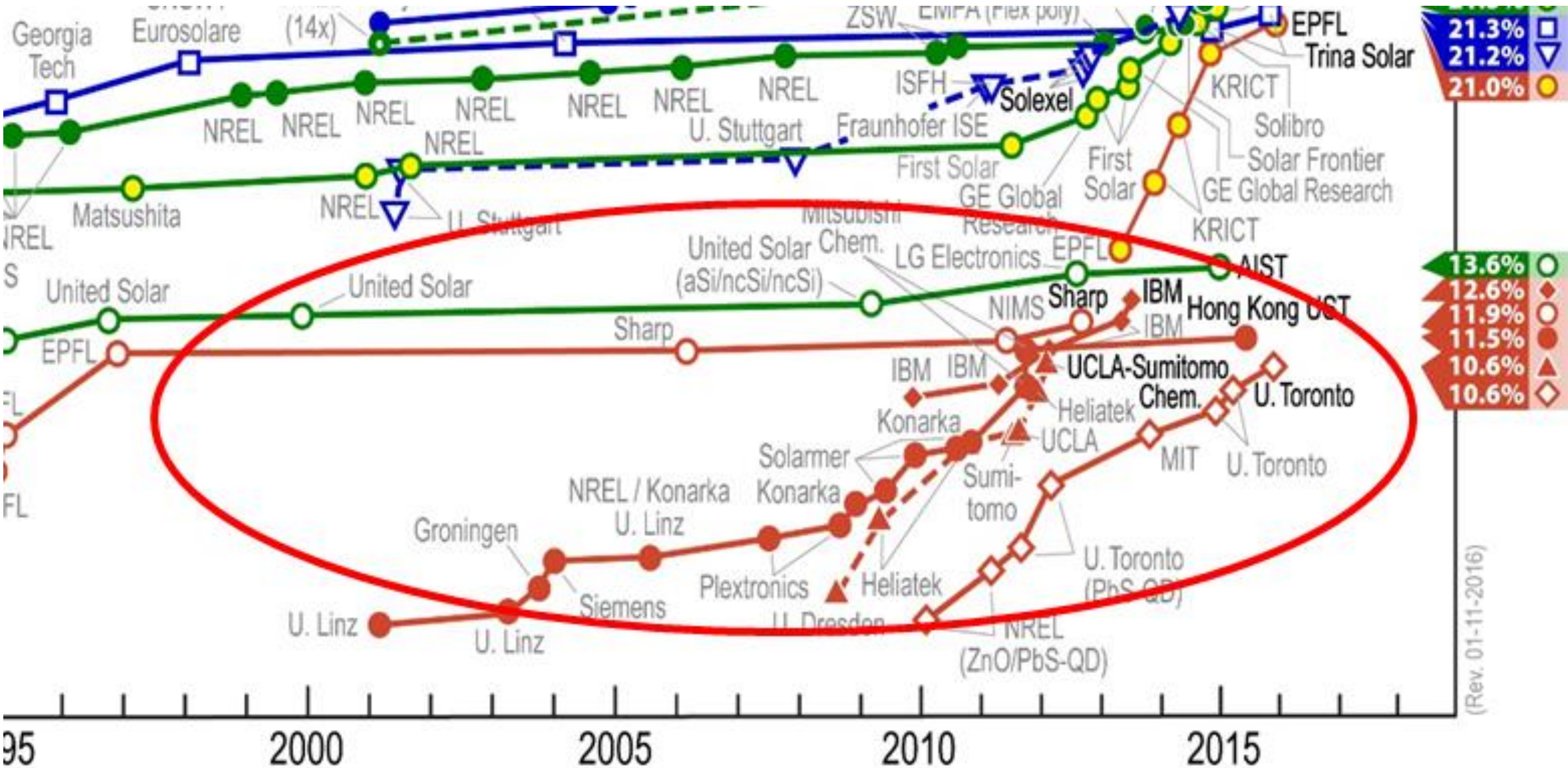


Source: modified after W. Hoffmann, EPIA and M. Green, UNSW



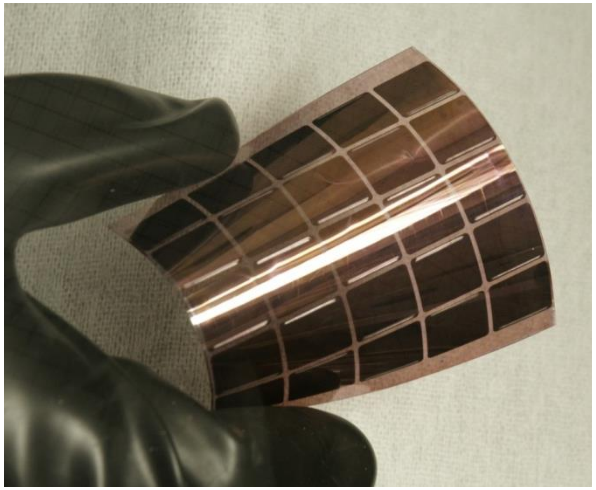
Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
Efficiency (%)
50
48
44
40
36
32
28
24
20
16
12
8
4
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
46.0%
44.4%
38.8%
37.9%
34.1%
31.6%
29.1%
28.8%
27.6%
27.5%
25.6%
25.0%
23.3%
22.3%
21.5%
21.3%
21.2%
21.0%
13.6%
12.6%
11.9%
11.5%
10.6%
10.6%
(Rev. 01-11-2016)

Source: NREL


Georgia Tech
Eurosolare
(14x)
ZSW
EMPA (Flex poly)
EPFL
Trina Solar
21.3%
21.2%
21.0%
NREL
ISFH
Solexel
KRICT
Solibro
Solar Frontier
GE Global Research
U. Stuttgart
Fraunhofer ISE
First Solar
GE Global Research
Matsushita
Mitsubishi Chem.
KRICT
United Solar
United Solar (aSi/ncSi/ncSi)
LG Electronics
EPFL
AIST
13.6%
12.6%
11.9%
11.5%
10.6%
10.6%
NIMS
Sharp
IBM
Hong Kong UST
UCLA-Sumitomo Chem.
U. Toronto
Heliatek
UCLA
Konarka
Solarmer
Sumi-tomo
MIT
NREL / Konarka
U. Linz
Groningen
Siemens
Plextronics
U. Dresden
U. Toronto (PbS-QD)
NREL (ZnO/PbS-QD)
(Rev. 01-11-2016)
2000
2005
2010
2015

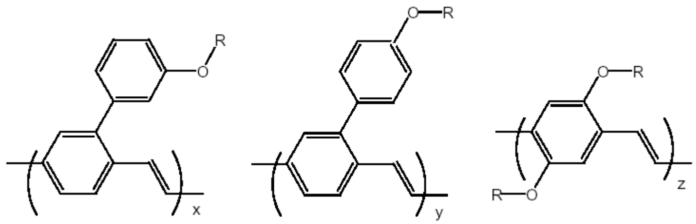
Source: NREL

Outline



Materials for Organic Semiconductor Devices

Conjugated Polymers



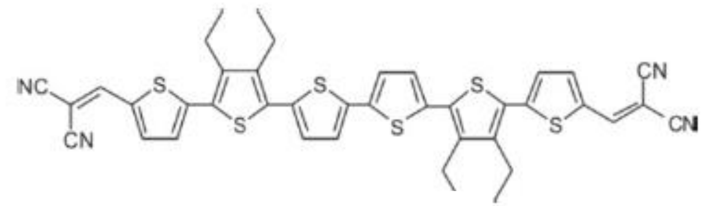
R = $(CH_2)_3CH(Me)(CH_2)_2CHMe_2$

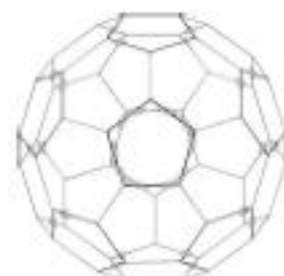
Merck (Covion) PPV Co-Polymers

Polyfluorene Sumitomo (Dow)
„Lumation“

Deposition from a solution
„Polymer Solar Cells)“

Small Molecules

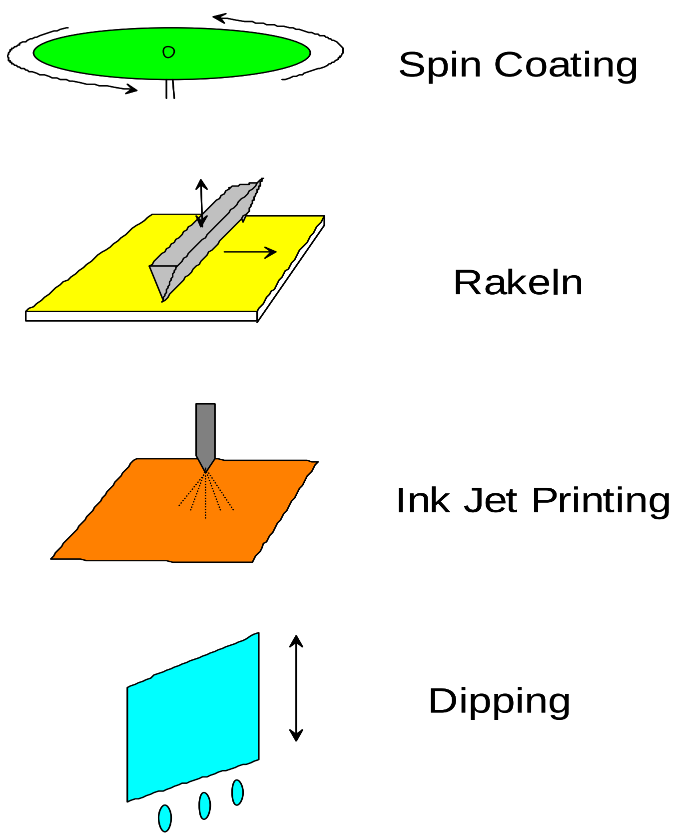




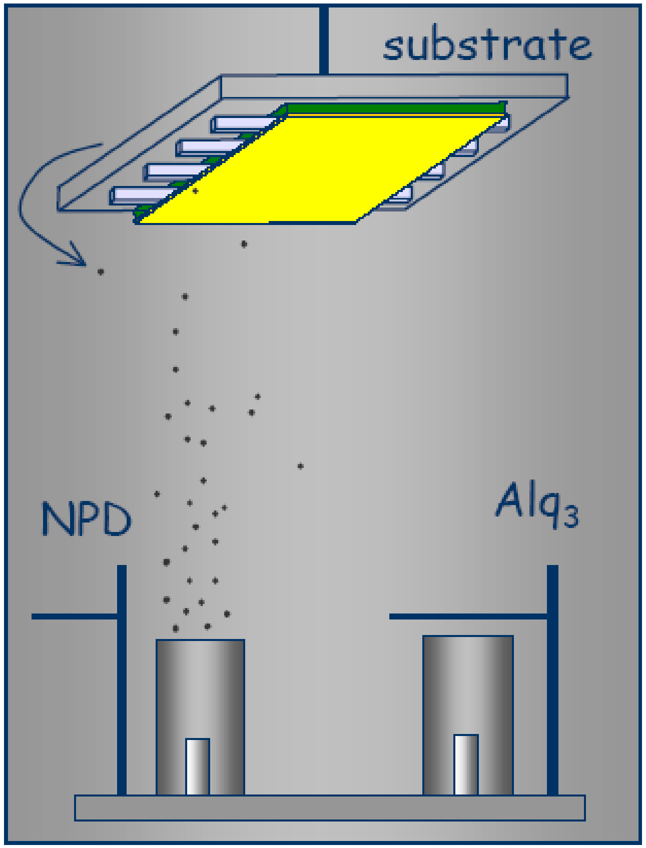
„Small Molecule Solar Cells “

Thin Film Deposition

Source: H. Antoniadis, Osram OS



Conjugated Polymers



Evaporation of small molecules

Thin film deposition in the laboratory

Polymer-Deposition in inert-gas
glove boxes by spin coating

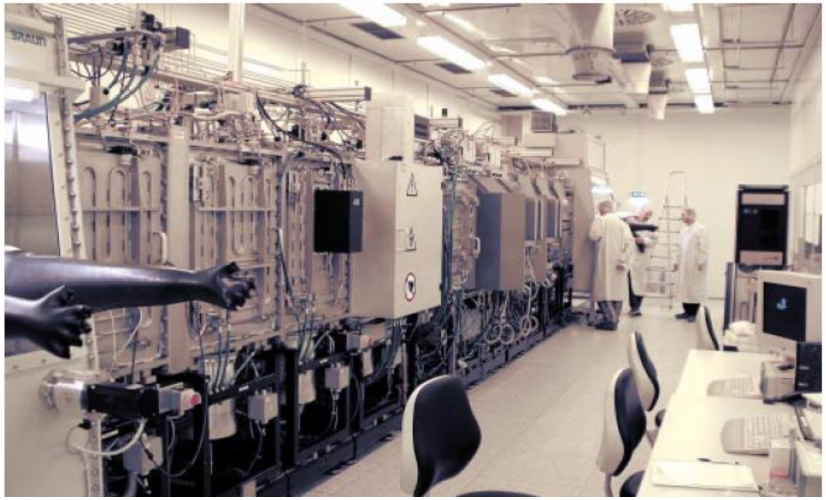
Evaporation chamber at LTI

Thin film coating/printing on a larger scale

300 mm roll-to-roll (R2R)-printing at KIT

Thin film deposition: Evaporation

OLED fabrication tools at IPMS



- VES400/13 in-line evaporation system
  Substrates up to 370 x 470 mm²

  12 linear evaporation sources for organic materials

  Supplier: AMAT

- SUNICEL plus200 cluster deposition system
  Substrates 200 x 200 mm², 150 or 200 mm wafer

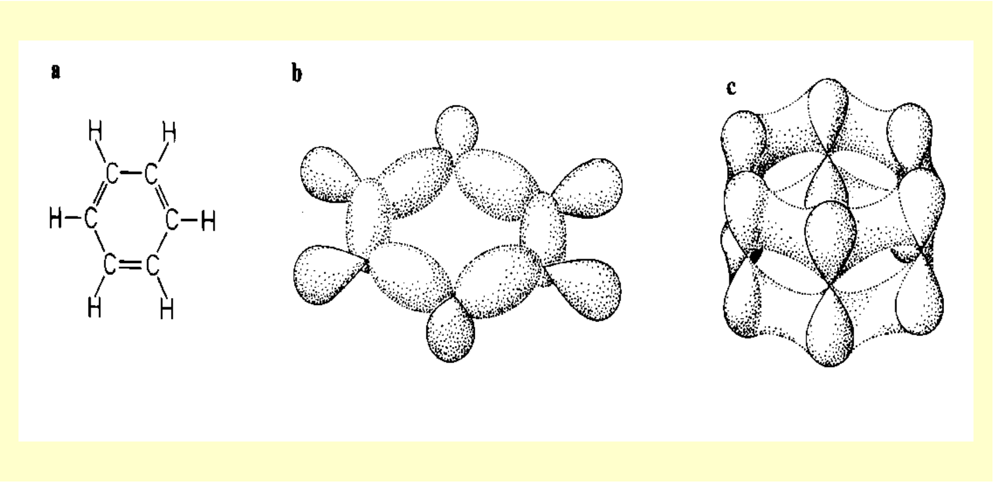
  12 + 1 evaporation sources for organic materials

  Supplier: Sunic System

Source: FhG IPMS, Dresden

Electronic states in molecules

→ delocalized π-electrons like in benzene are needed

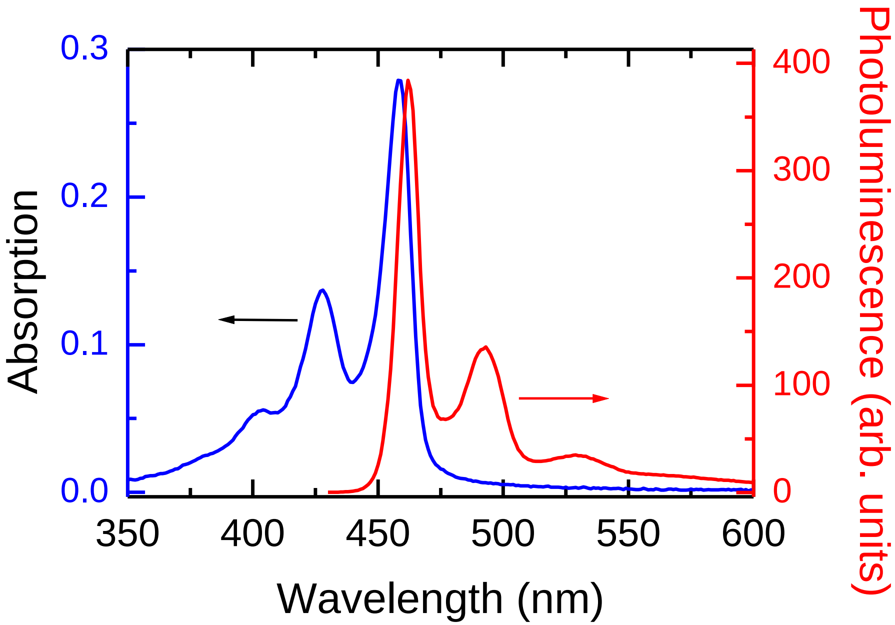


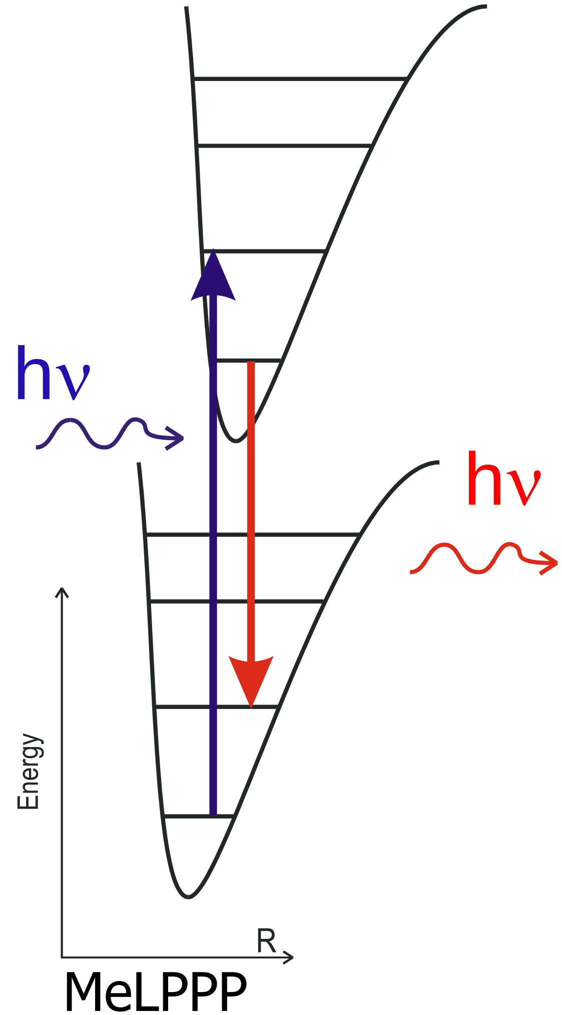
sp^2-
hybrid orbitals

p_z-orbitals
form π-orbitals

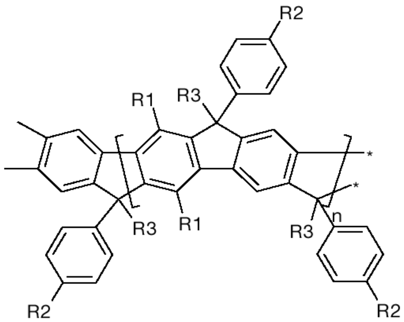
Electronic and Optoelectronic Properties?

Emission vs. Absorption



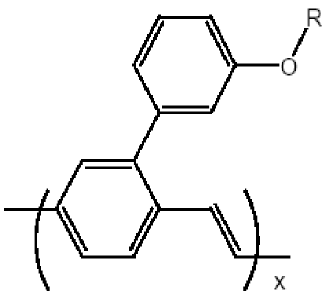


-Spectrally broad (?) emission bands
-Spectrally narrow(?) absorption bands

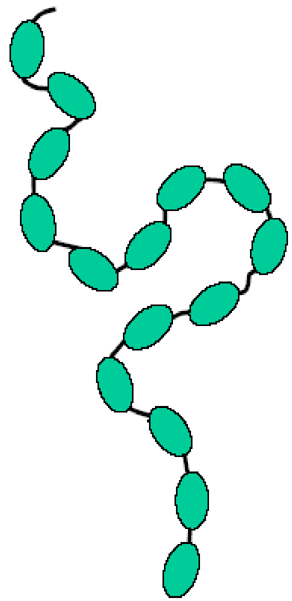


Localized states in a *disordered* organic semiconductors

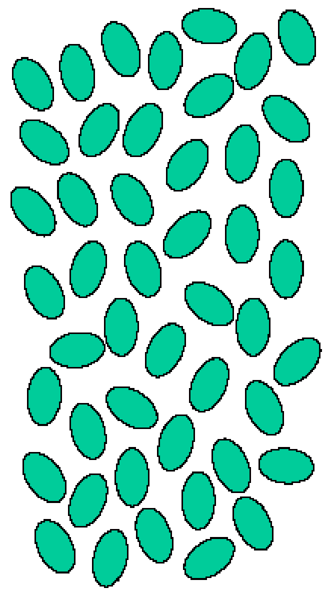
Electronic transport in OLED & OPV materials is determined by the *localized* nature of the electronic states.



R = $(CH_2)_3CH(Me)(CH_2)_2CHMe$

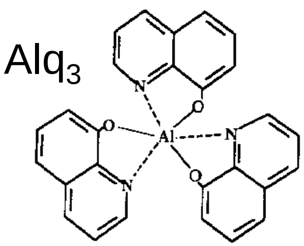


Functional Polymers

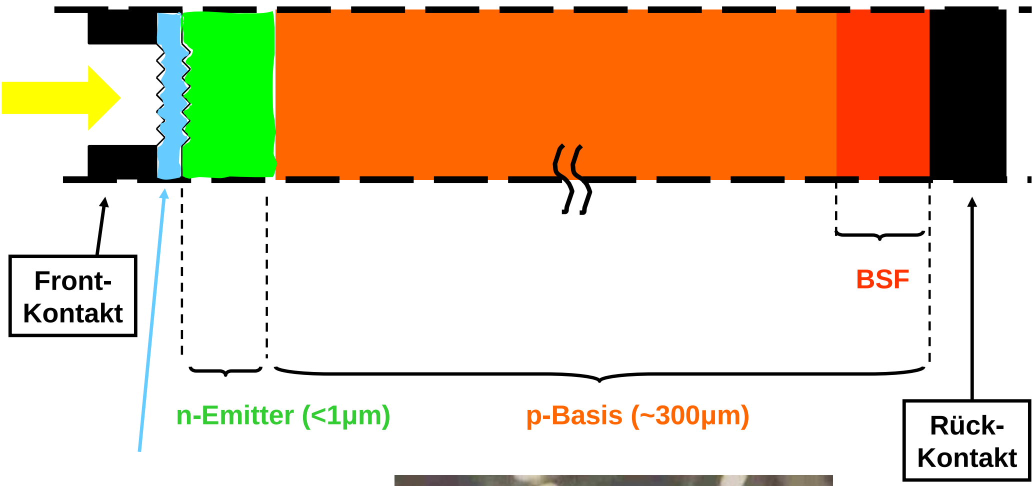


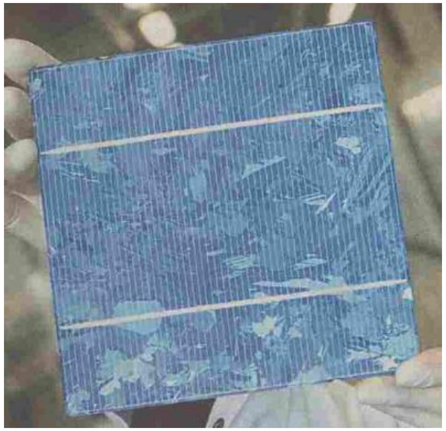
Small Molecules

Alq$_3$



Reminder:
Operational principles of a silicon solar cell





Light is absorbed

↓

Generation of mobile carriers

↓

Seperation of carriers (e.g. with pn-junction)

↓

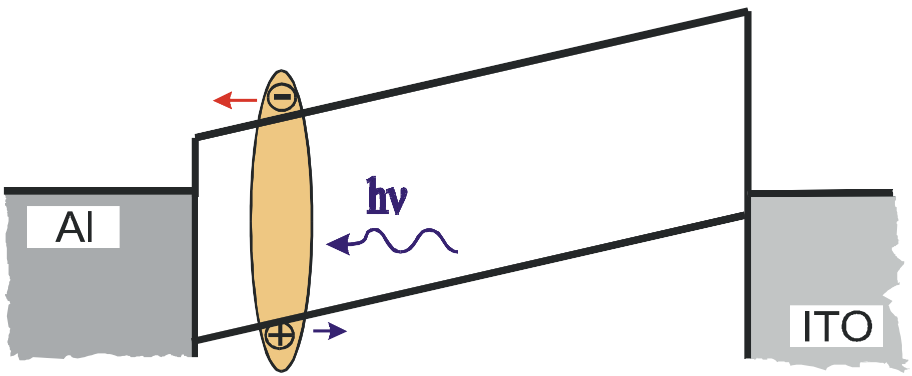
induces voltage at contacts

↓

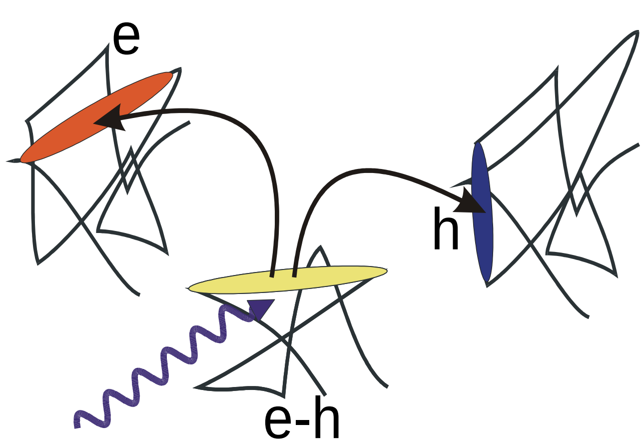
Current flow through external load

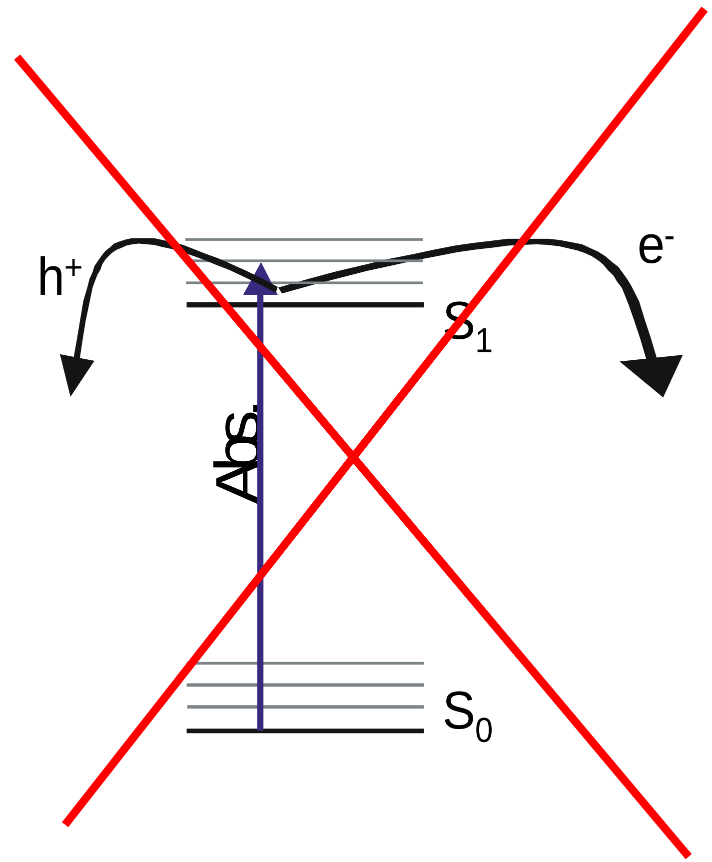
The problem of exciton dissociation

Device Scheme:



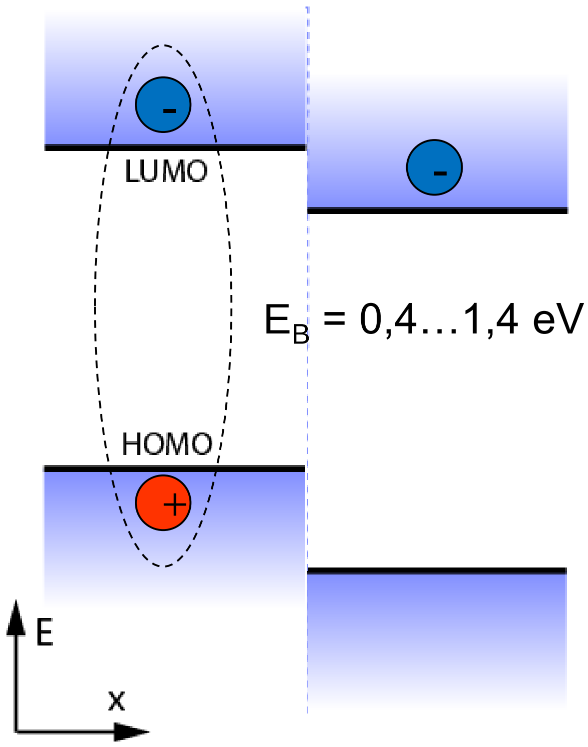
Dissociation process:





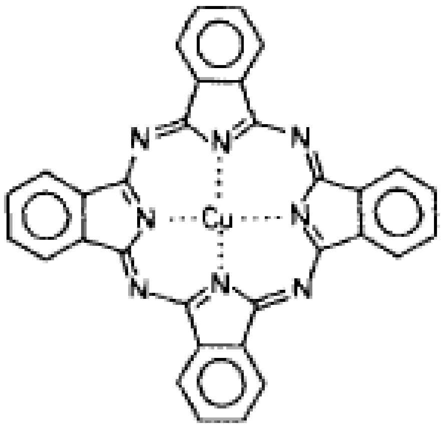
Binding energy is
on the order of 0.5 eV

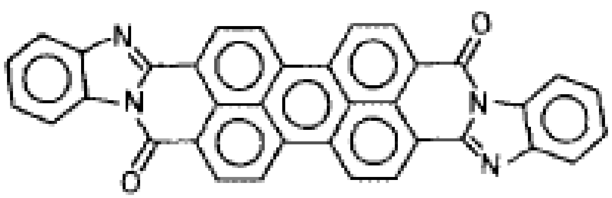
Organic Solar Cells



We need heterojunctions!

History: The Tang-cell: First demonstration of efficient dissociation at an internal interface





C.W. Tang, Kodak, 1985
1 % at AM 2

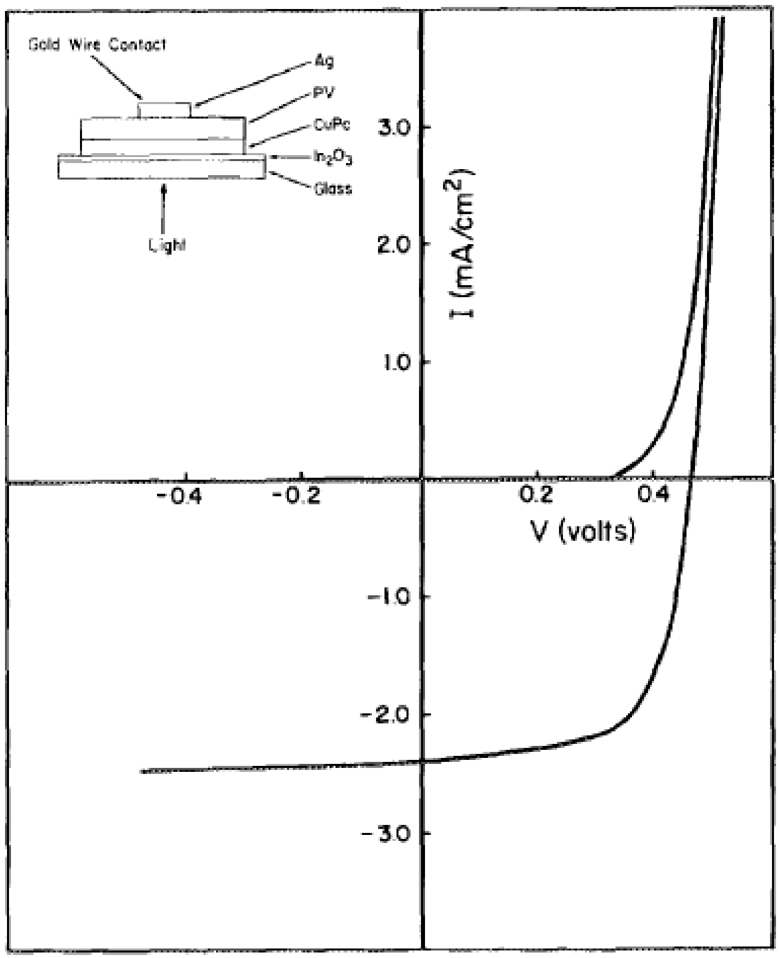


FIG. 1. Configuration and current-voltage characteristics of an ITO/CuPc (250 Å)/PV(450 Å)/Ag cell.

Tang, C. W. *"Two Layer Organic Photovoltaic Cell"* , Appl. Phys. Lett. 48, 183 (1986).

Outline

6.8 Organic and Perovskite Solar Cells

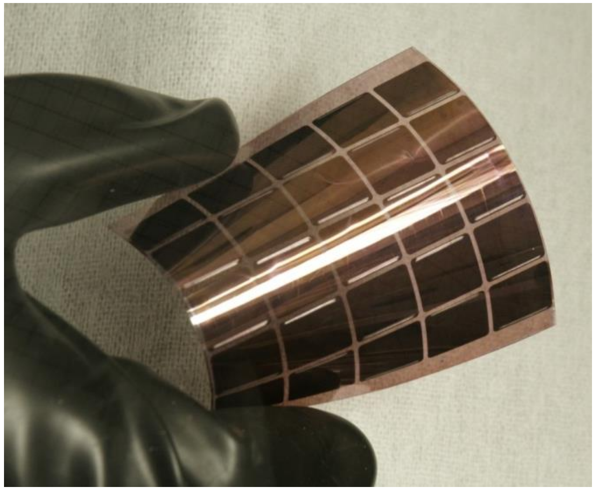
6.8.1 Organic Semiconductors

6.8.2 Low Bandgap Materials

6.8.3 Semitransparent and Tandem Solar Cells

6.8.4 OPV Industry

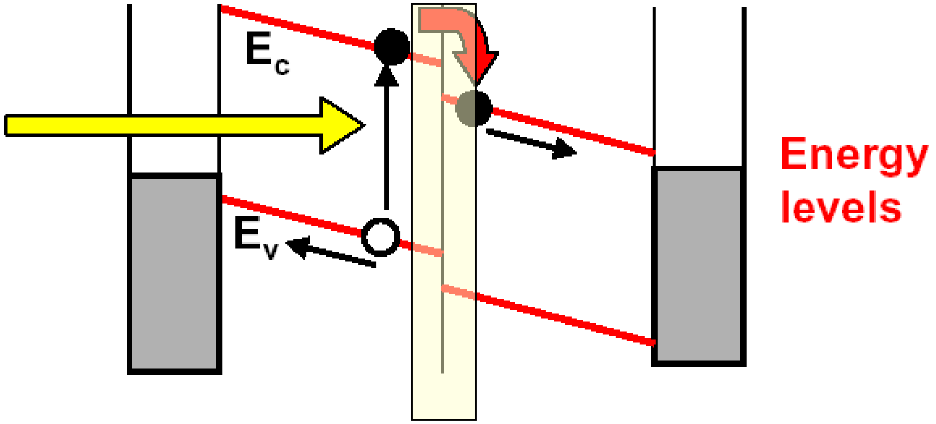
6.8.5 Perovskite Solar Cells



From a bilayer to a bulk heterojunction

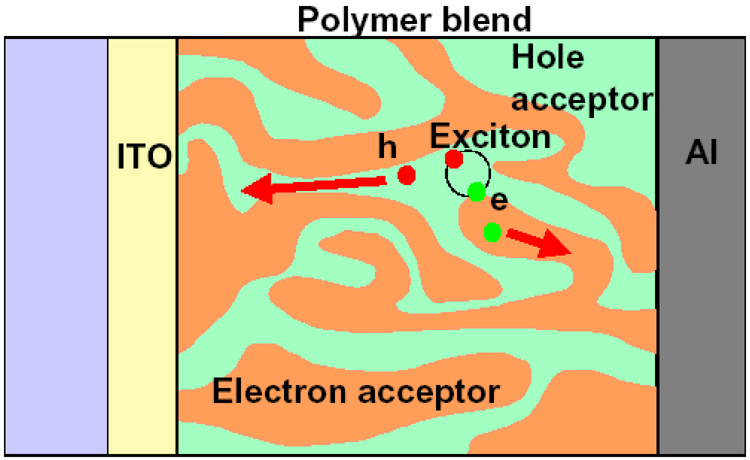
Bilayer:

-the active layer of the device is limited to the diffusion length (10-20 nm)
-only the interface is contributing to the quantum efficiency

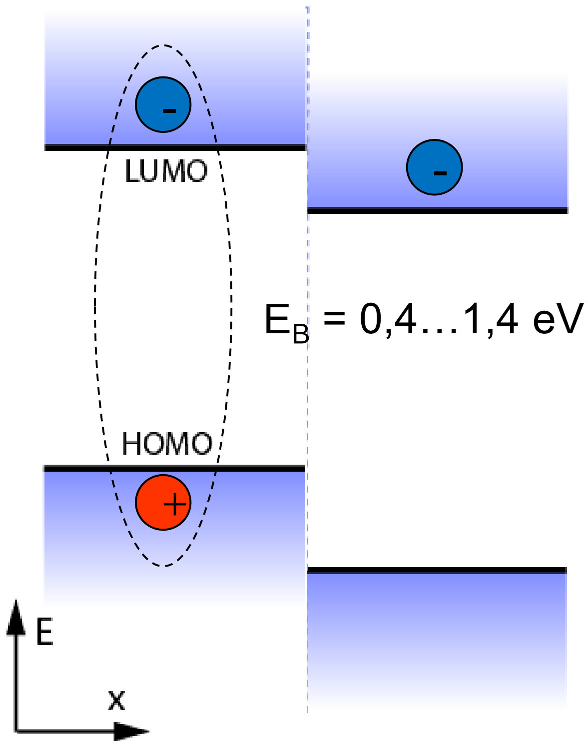


„Bulk-Heterojunctions“
„Interpenetrating Networks“

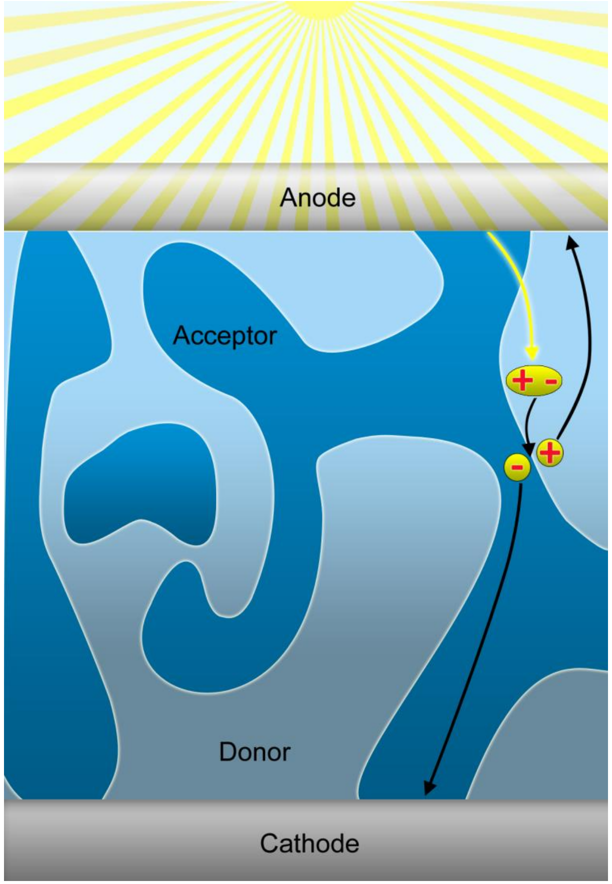
The whole layer is contributing to the photocurrent generation.



Organic Solar Cells



Bilayer Heterojunction



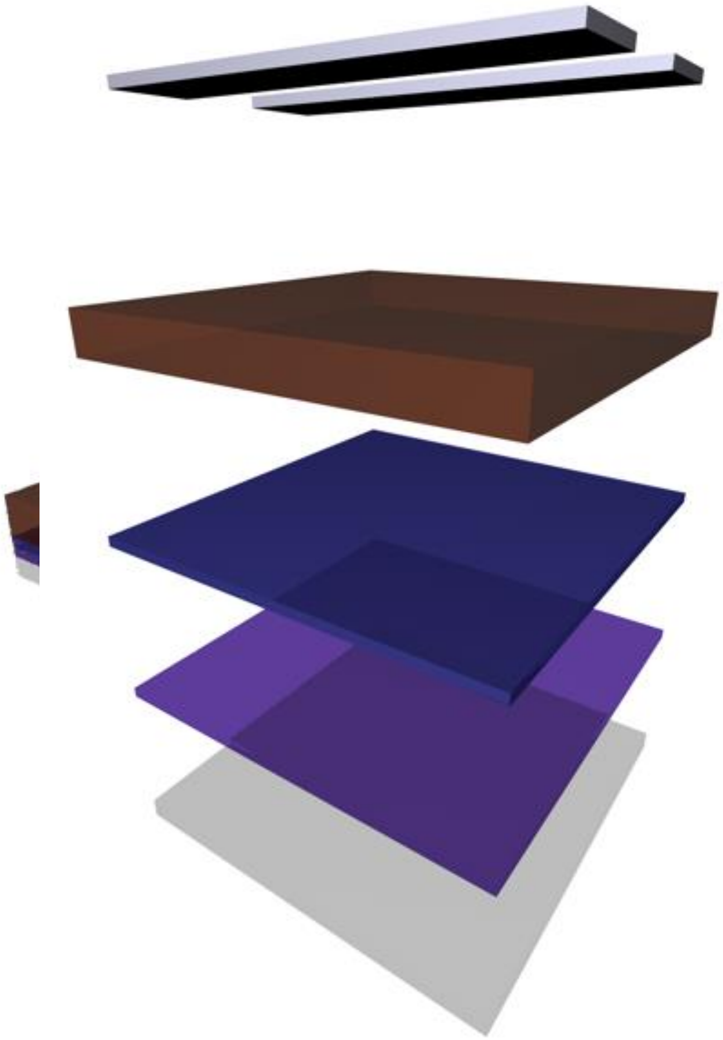
Bulk Heterojunction

A particularly well working combination: Fullerenes + Conjugated Polymers

N.S. Sariciftci, L. Smilowitz, A. J. Heeger, F. Wudl, Science, 258, 1474 (1992)

S. Morita, A.Zakhidov, K. Yoshino, Solid State. Commun. 82, 249 (1992)

Organic Solar Cells



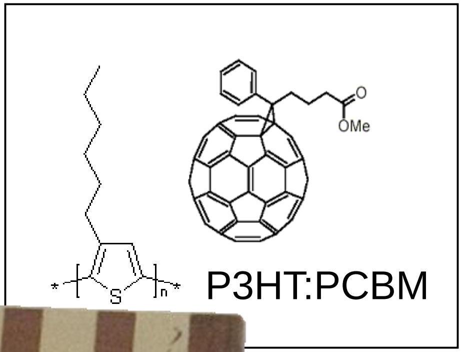
Cathode
200 nm

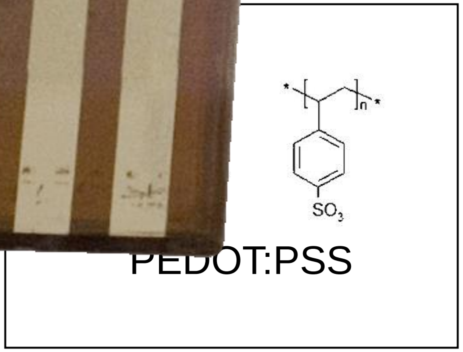
Absorber
200 nm

Hole conductor
20 nm

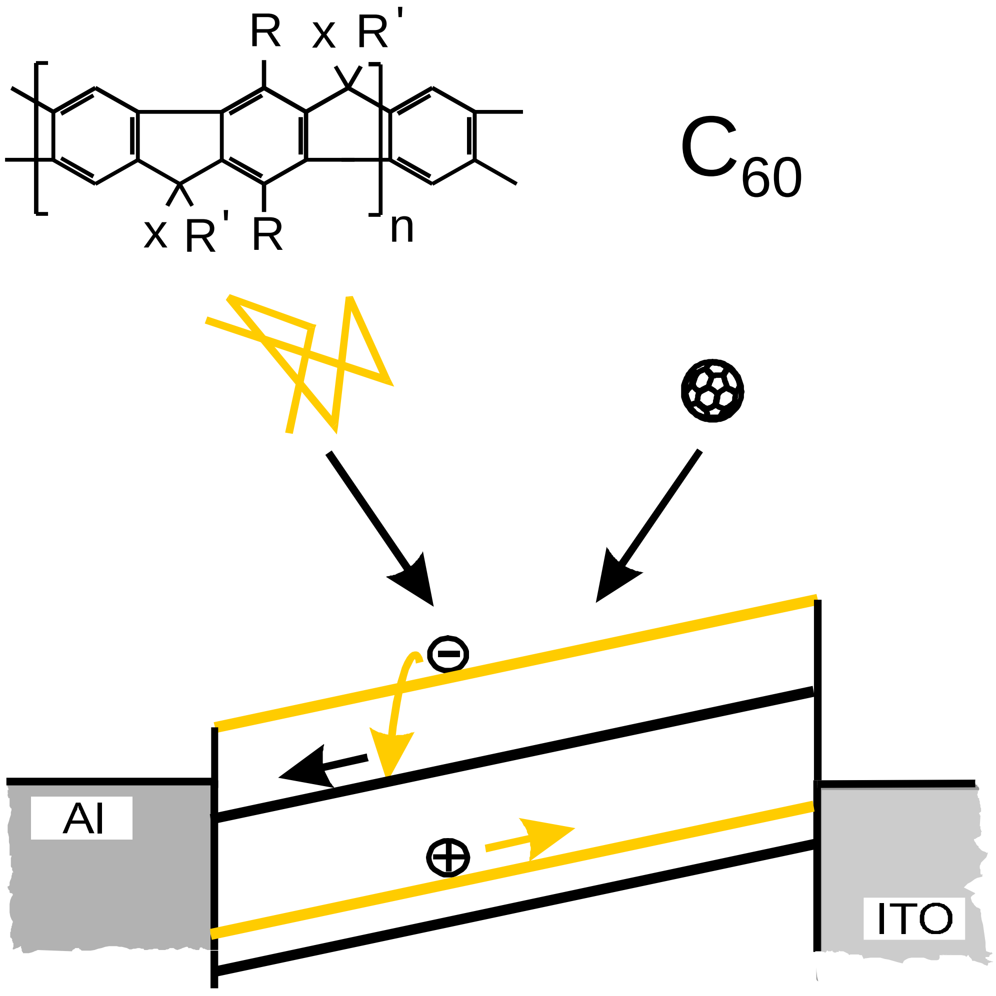
Anode (ITO)
125 nm

Substrate (Glass)

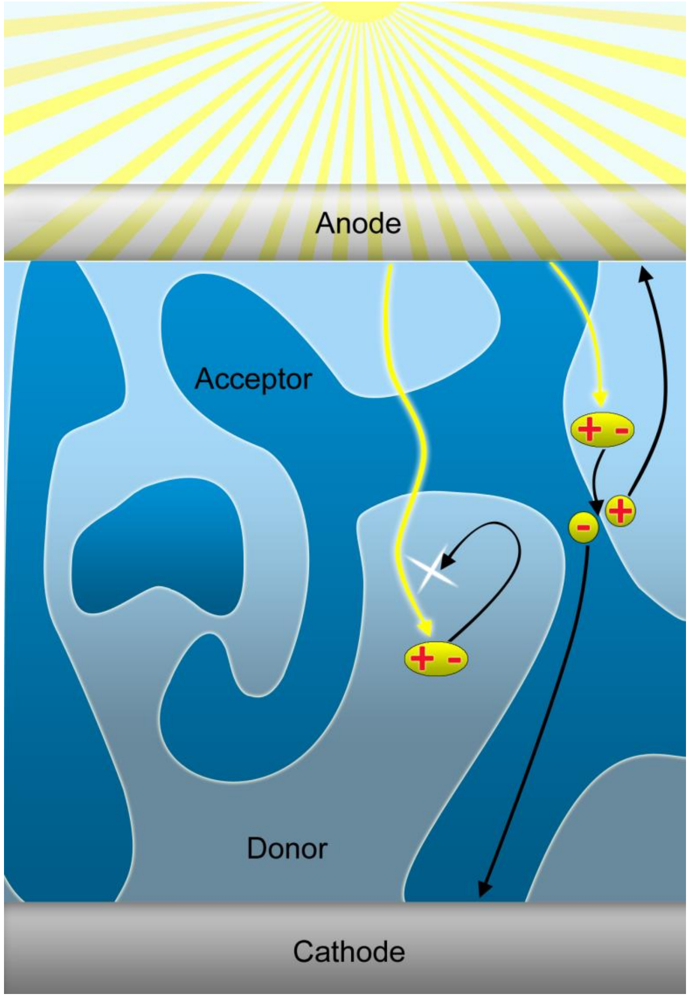




Electronic band diagram of a bulk heterojunction solar cell



Nanostructure is crucial ..
… but depends on pretty much every deposition parameter



ex-situ (dried samples)

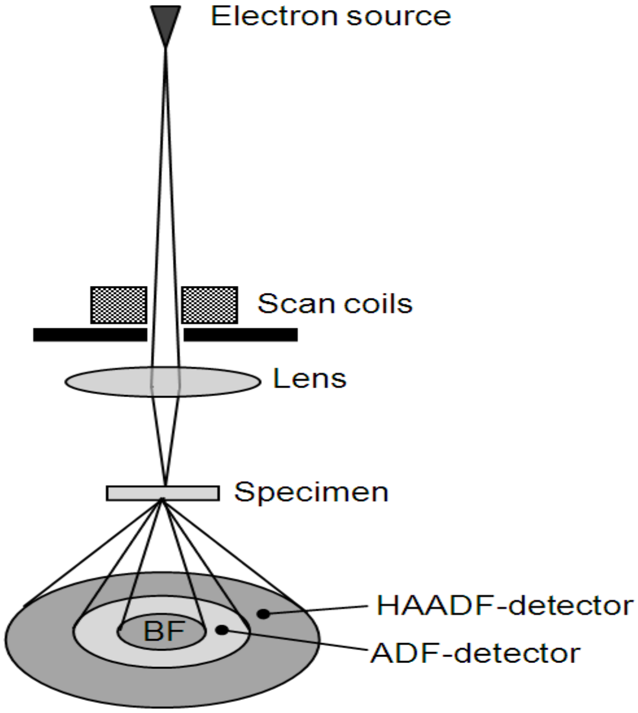
and

in-situ /online (during deposition/drying)

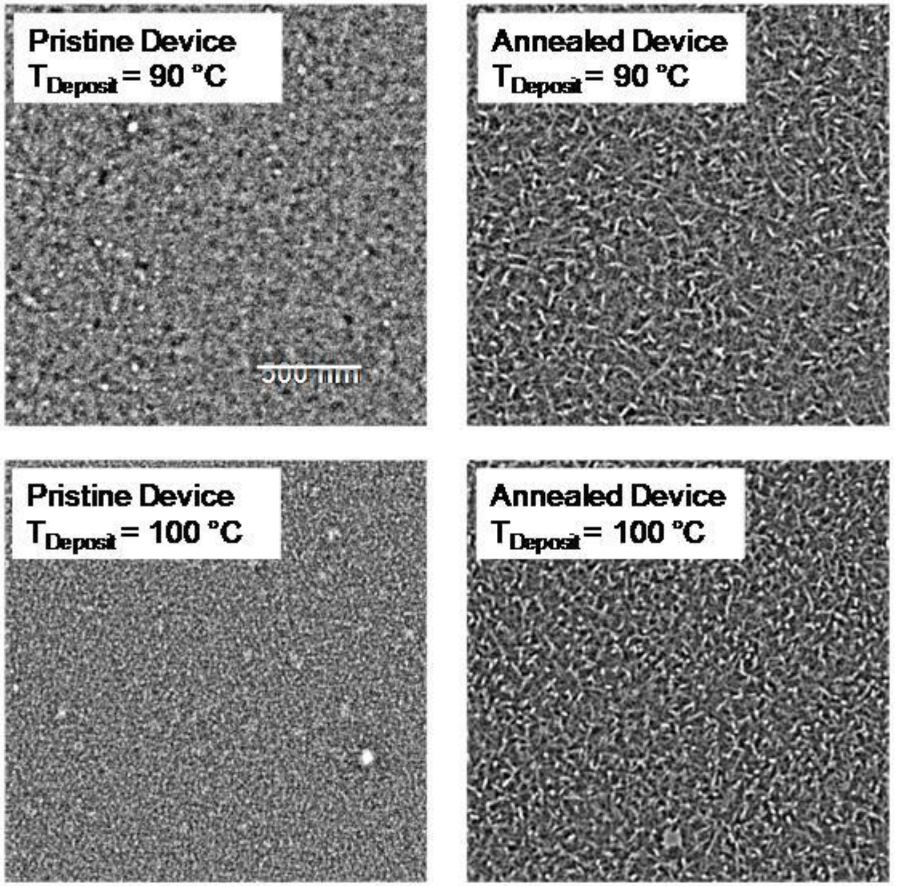
are needed

Uli Lemmer

Nanomorphology of polymeric solar cells



HAADF:
High angle annular dark field

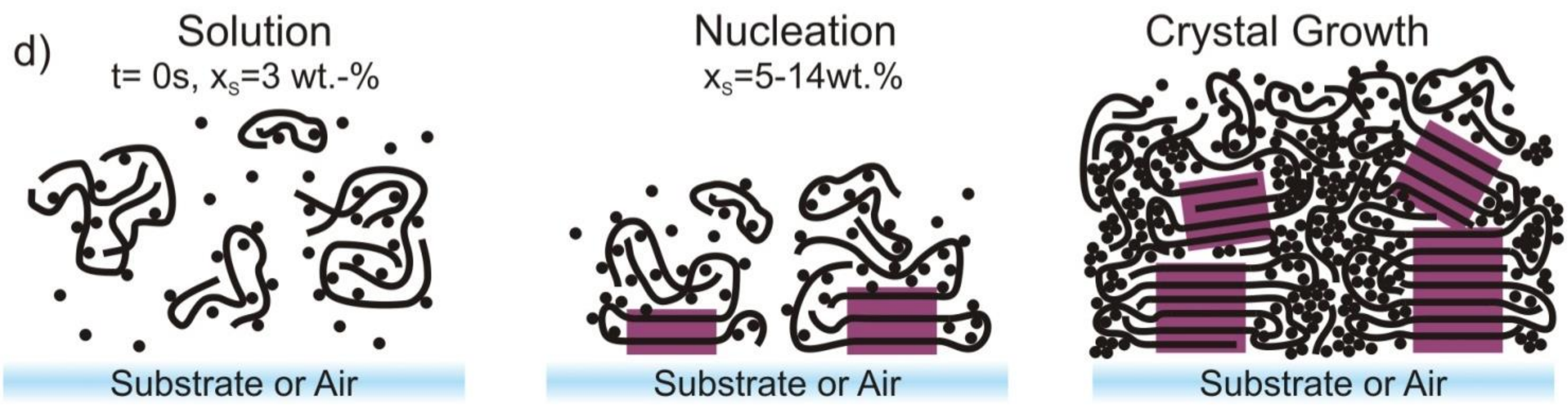


HAADF STEM images after bandpass filtering between 8-80 nm spatial wavelength

Evolution of polymer-fullerene structure

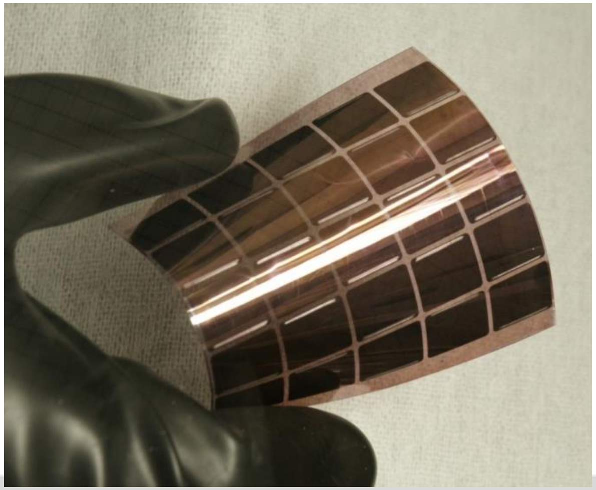
Evolution of structure:

- P3HT nucleation at interface (substrate or/and air)
- P3HT crystal growth (squeezes out PCBM / increasing orientation distribution)
- PCBM enriches in the amorphous P3HT regions and aggregates

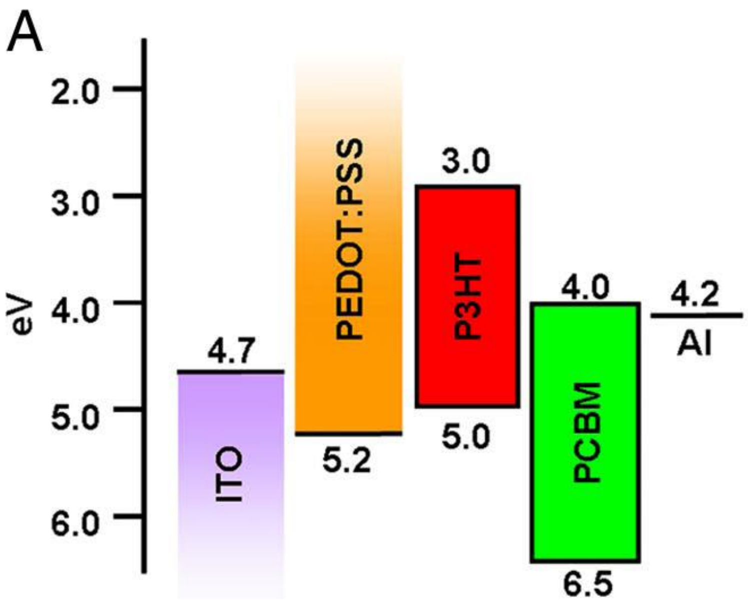


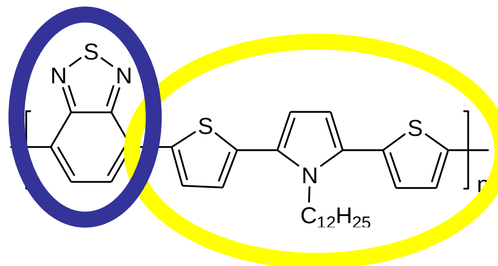
B. Schmidt-Hansberg, M. Sanyal, M.F.G. Klein, M. Pfaff, N. Schnabel, S. Jaiser, A. Vorobiev, E. Müller, A. Colsmann, P. Scharfer, D. Gerthsen, U. ***Lemmer, E. Barrena, W. Schabel***
Moving through the phase diagram: morphology formation in solution cast polymer–fullerene blend films for organic solar cells
*ACS Nano 5, 8579–8590 (**2011**)*

Outline

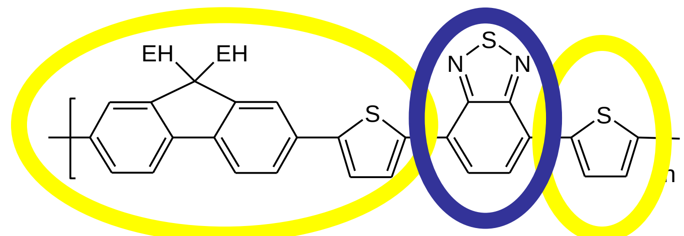


Low bandgap polymers



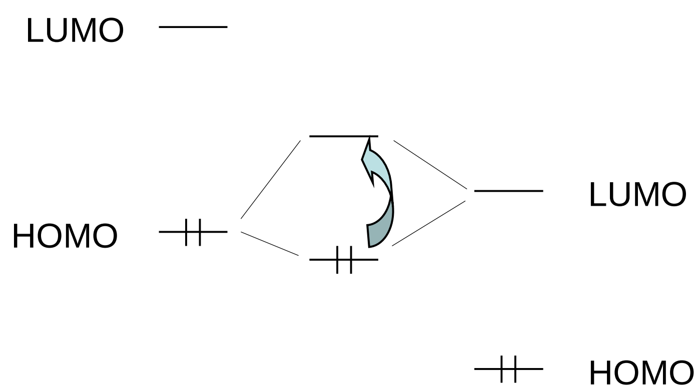


PTPTB



PFDTBT

Donor + Acceptor → internal charge transfer complex in which the **whole** polymer acts as an electron donor



Low bandgap polymers

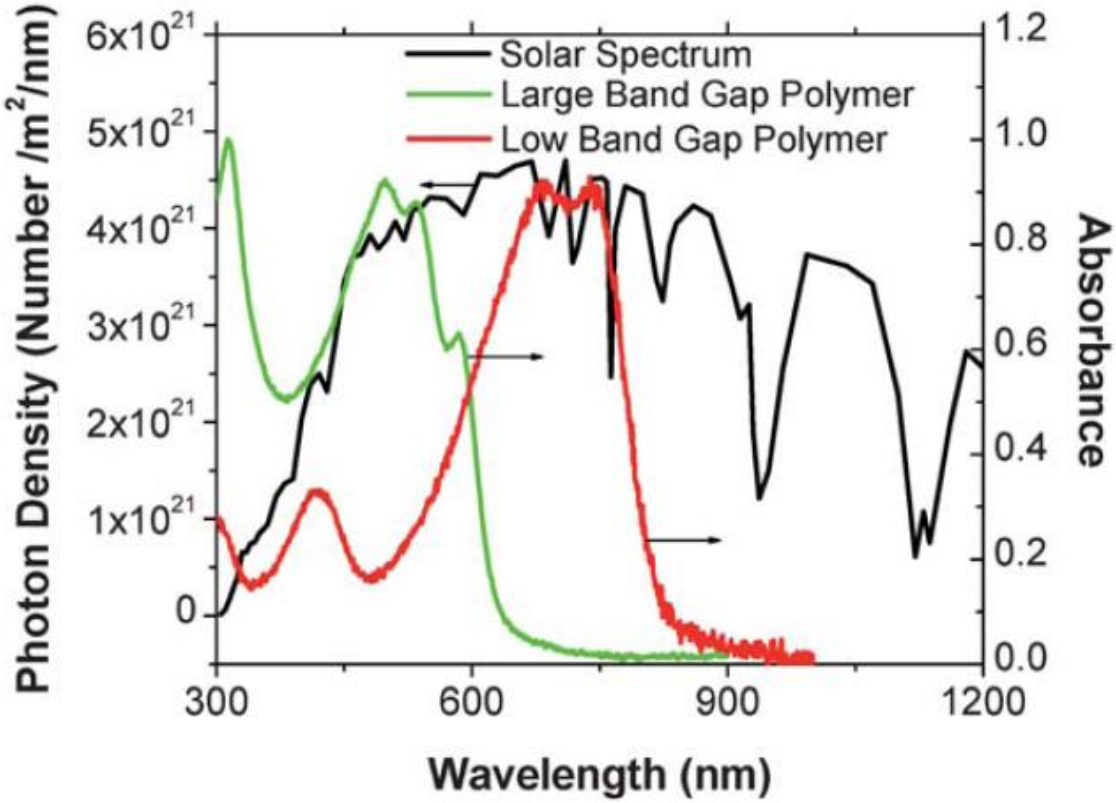
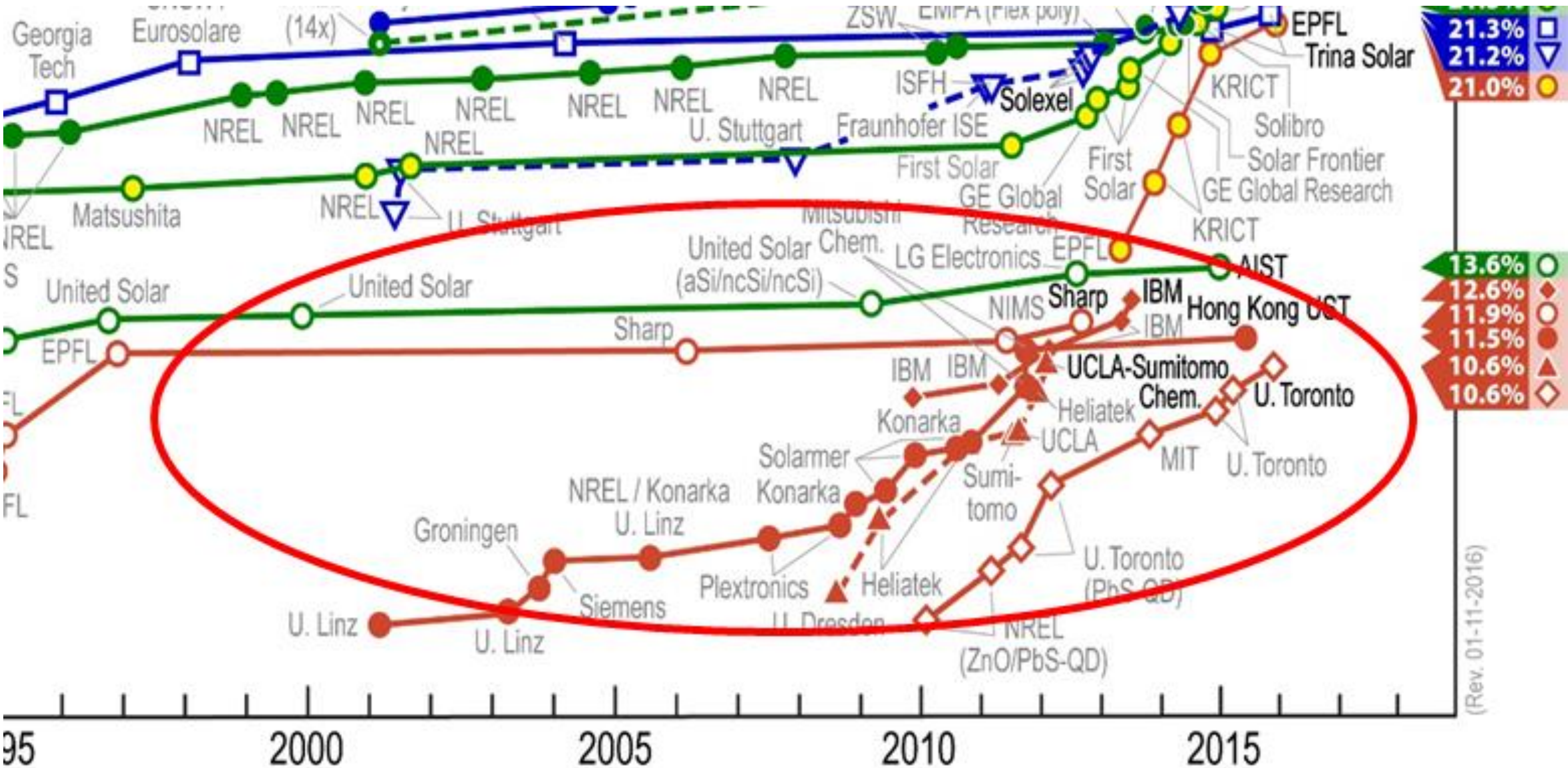


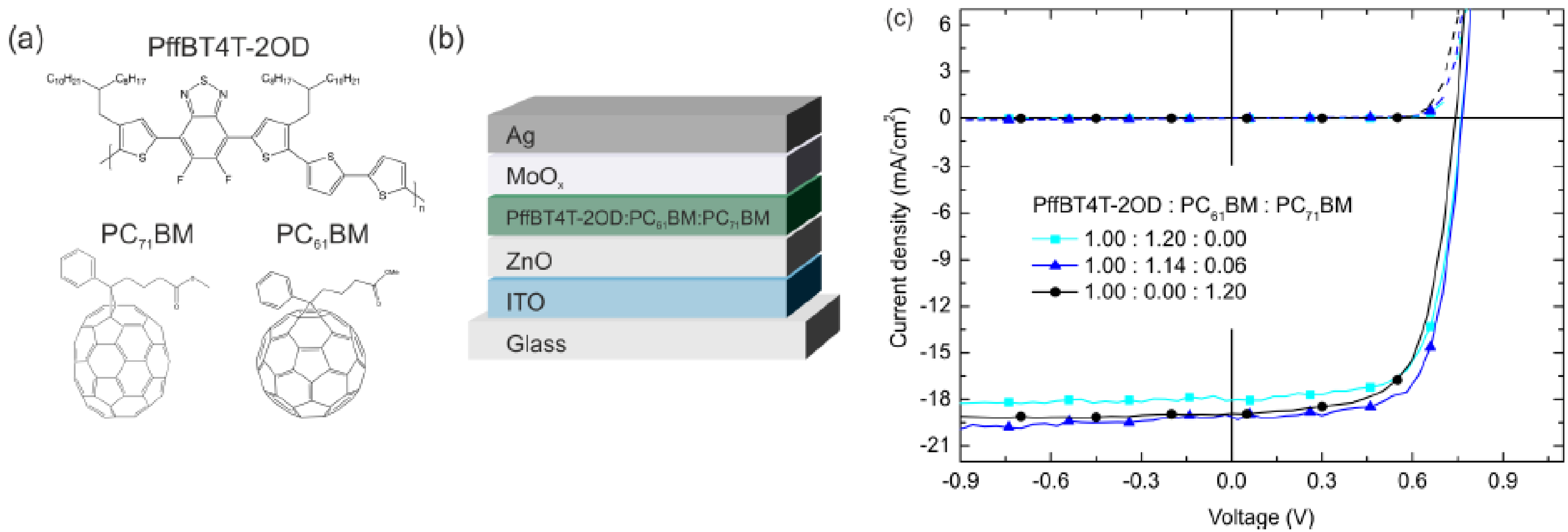
Fig. 1 Absorbance of P3HT a large band gap polymer (green) and PSBTBT a low band gap polymer (red) is compared to the solar spectrum which spans from 300–1200 nm and even beyond.

Source: Sista et al., Energy Environ. Sci. 4, 1606 (2011)


Georgia Tech
Eurosolare
(14x)
ZSW
EPFL
Trina Solar
21.3%
21.2%
21.0%
NREL
ISFH
Solexel
KRICT
Solibro
Solar Frontier
GE Global Research
U. Stuttgart
Fraunhofer ISE
First Solar
GE Global Research
Matsushita
LG Electronics
EPFL
AIST
United Solar
United Solar (aSi/ncSi/ncSi)
Mitsubishi Chem.
13.6%
12.6%
11.9%
11.5%
10.6%
10.6%
NIMS
Sharp
IBM
Hong Kong UST
UCLA-Sumitomo Chem.
U. Toronto
Heliatek
Konarka
UCLA
MIT
Solarmer
Sumi-tomo
Groningen
NREL / Konarka
U. Linz
Siemens
Plextronics
U. Dresden
U. Toronto (PbS-QD)
NREL (ZnO/PbS-QD)
(Rev. 01-11-2016)
2000
2005
2010
2015

Source: NREL

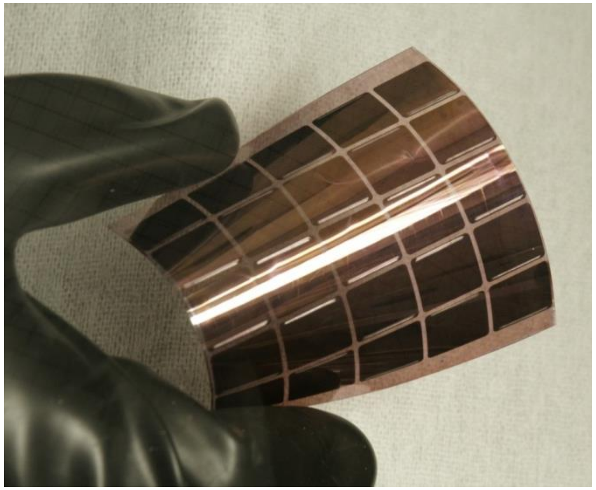
Efficient low band organic solar cells @ LTI (2016)



PffBT4T-2OD: $PC_{61}BM:PC_{71}BM$	J_{SC} (mA/cm²)	V_{OC} (mV)	FF (%)	PCE (%)
1.00 : 1.20 : 0.00	17.9 ± 0.1	766 ± 4	69 ± 1	9.4 ± 0.1 (9.5)
1.00 : 1.14 : 0.06	18.8 ± 0.5	765 ± 3	70 ± 2	10.1 ± 0.1 (10.2)
1.00 : 0.00 : 1.20	18.6 ± 0.2	741 ± 2	67 ± 1	9.2 ± 0.1 (9.4)

J. Czolk (submitted)

Outline

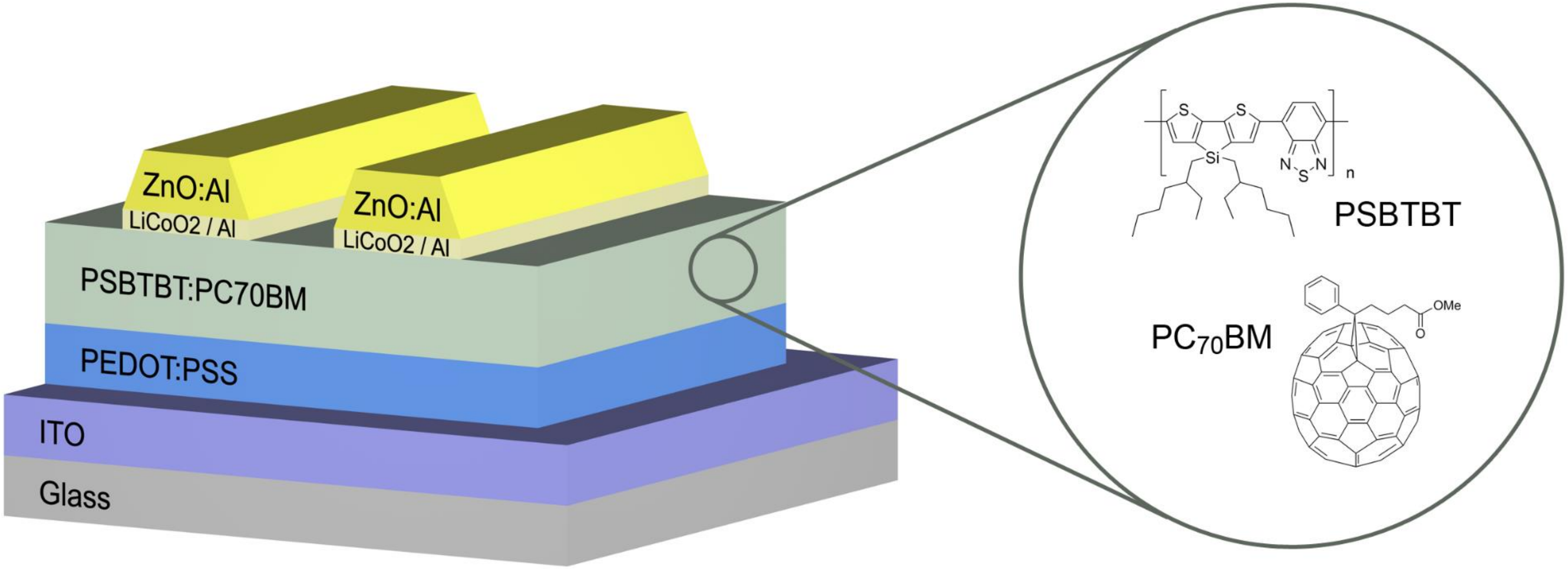


Semitransparent solar cells

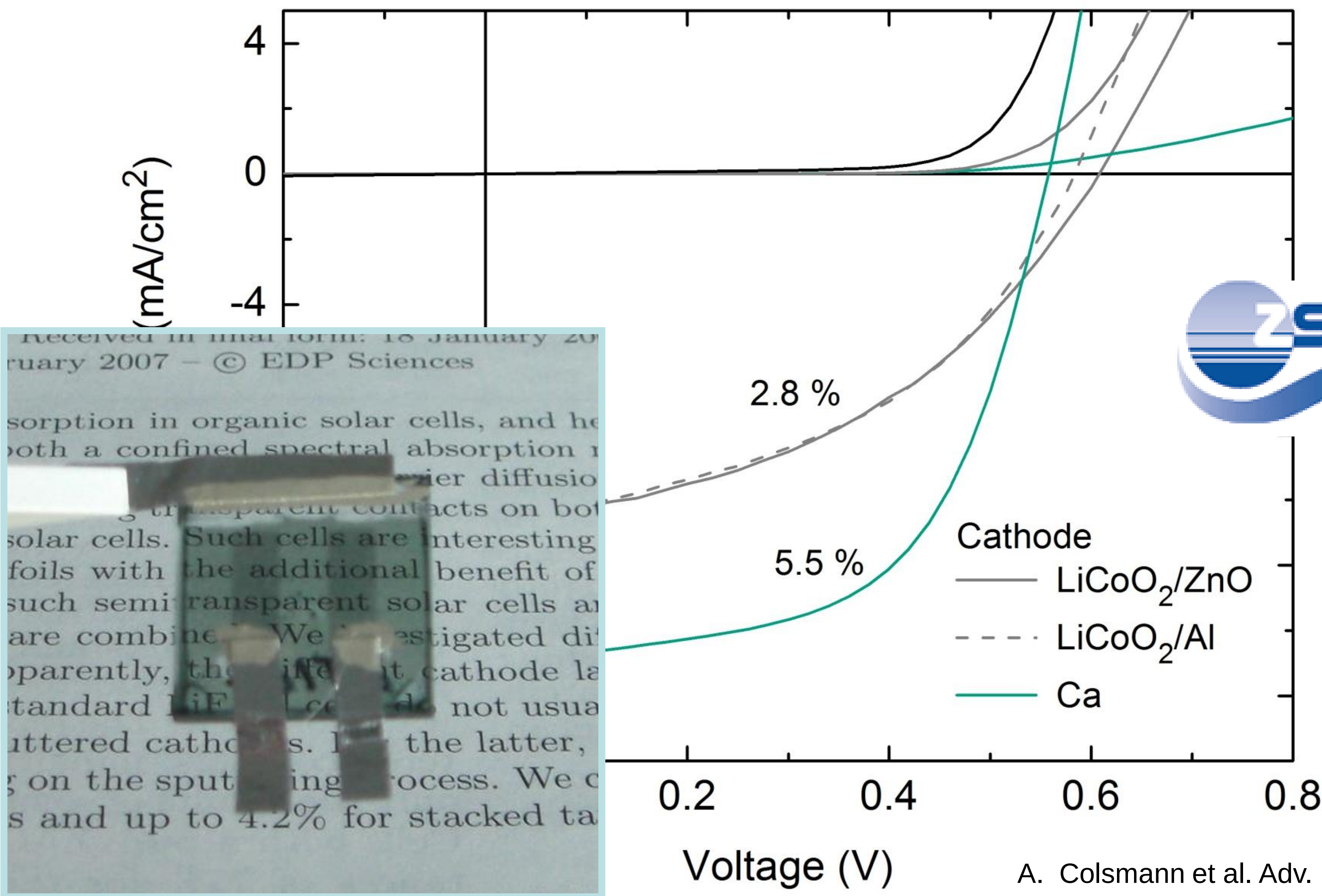
Source: Heliatek

Semi-transparent solar cells

Collaboration with J. Hanisch et al., ZSW Stuttgart

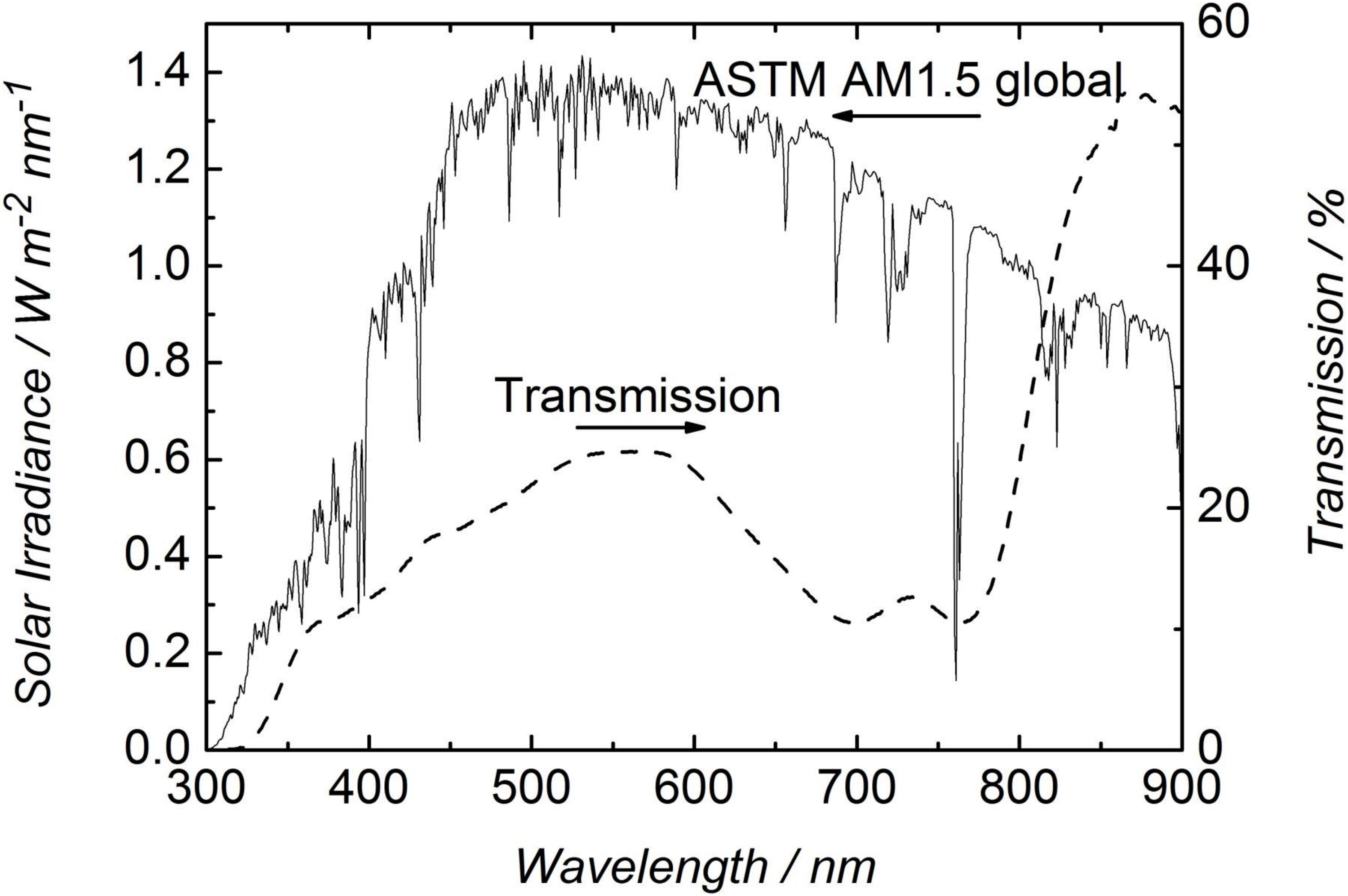


Semi-transparent solar cells

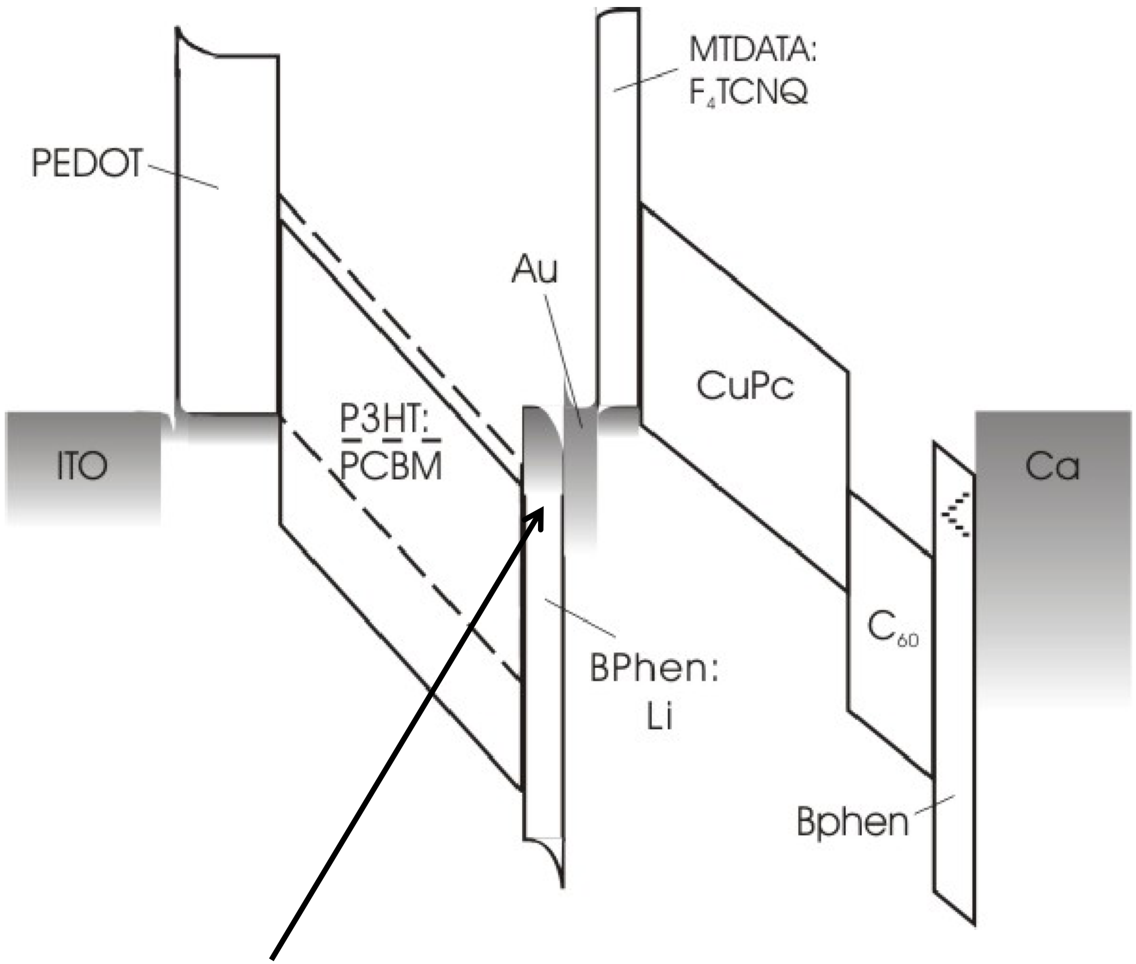


A. Colsmann et al. Adv. Energy Mat. (DOI: 10.1002/aenm.201000089)

PSBTBT Transmission vs. Solar Spectrum

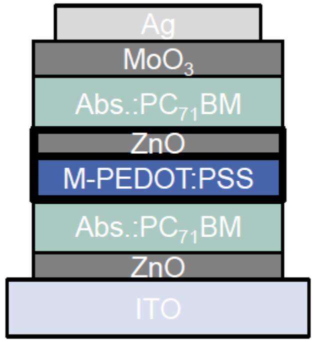


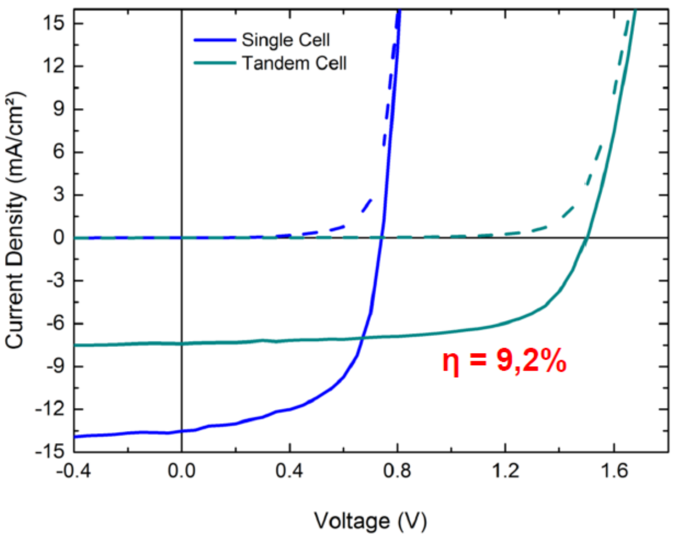
Energy band diagram of an organic tandem solar cell

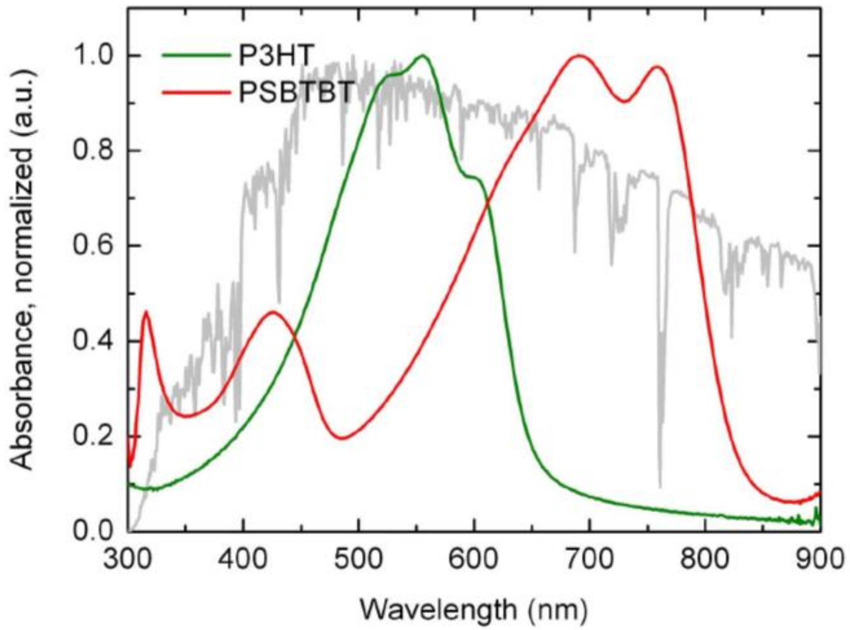


p- and n- doped intermediate layers are necessary

Organic tandem solar cell

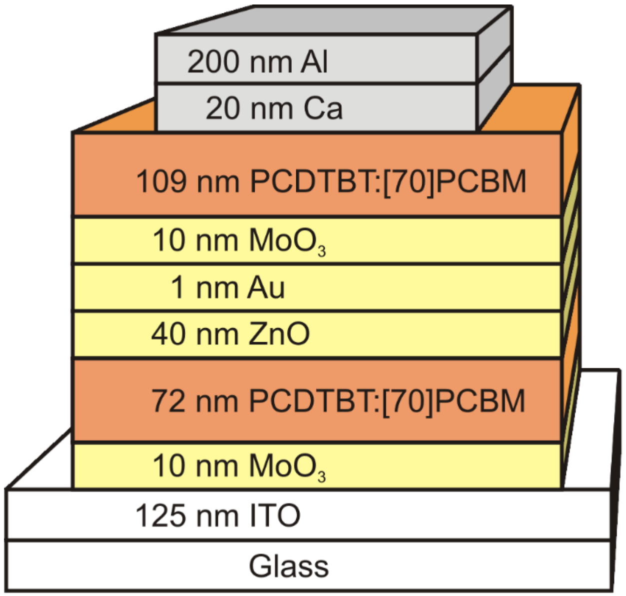


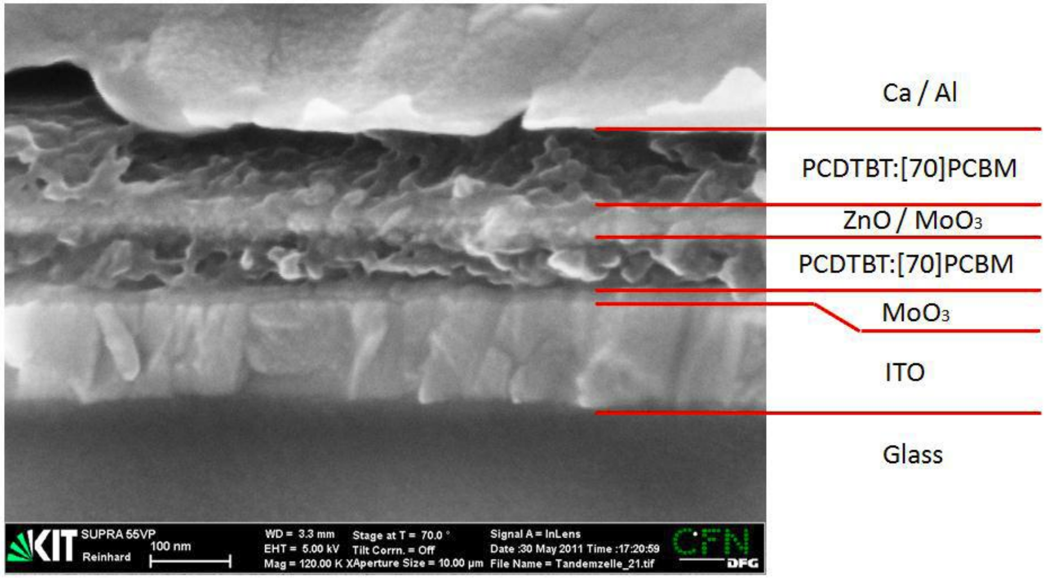


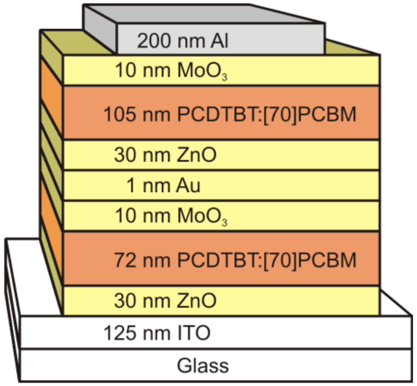


Metal oxide interlayers

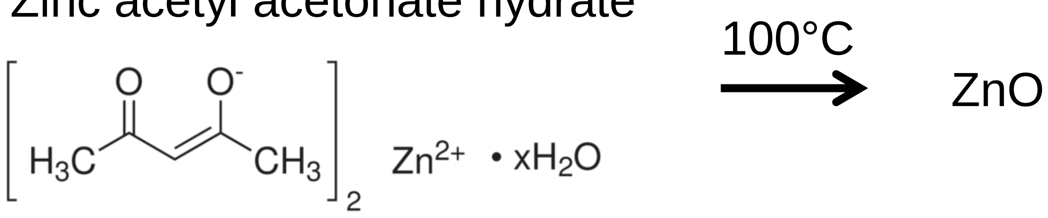
Karlsruhe Institute of Technology





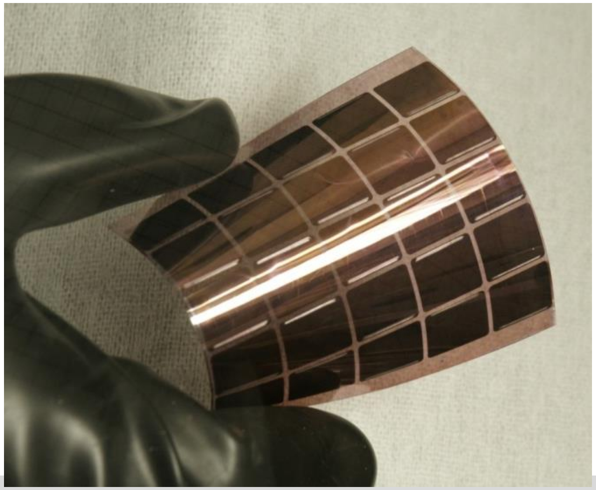


Zinc acetyl acetonate hydrate



[A. Pütz, Org. Electr. 13 (2012) 2696–2701]

Outline



Company Overview

KONARKA®

- Founded in 2001 as spin-out of UMass and University of CA
- Leading IP position with nearly 350 patents and global filings
- Strong 100+ person team with technical and industrial expertise
- $150+ private funding raised to-date, $20M government grants
- Global presence with staff in US, Germany, Austria, & China

Headquarters:
Lowell, MA

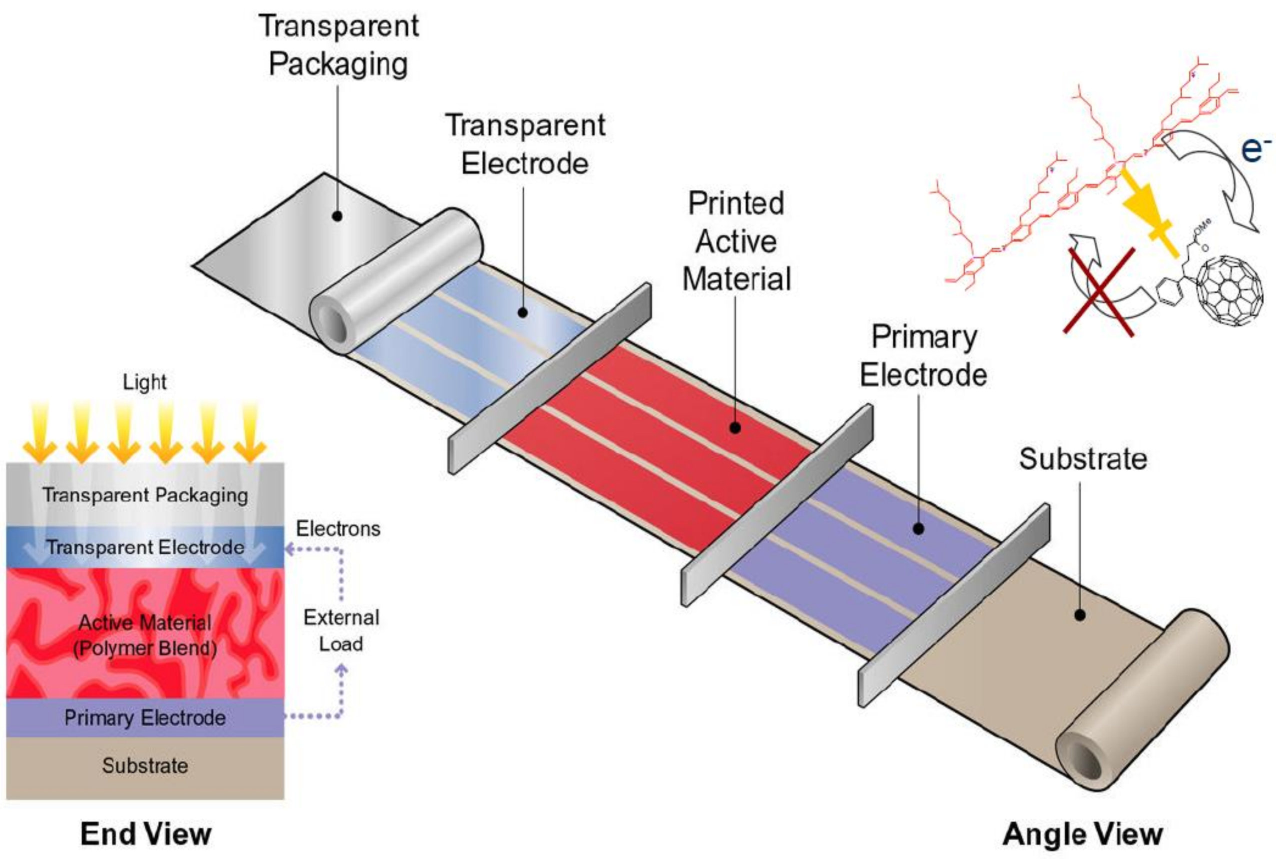
Production
New Bedford, MA

Nurnberg, Germany

Linz, Austria

Source: www.konarka.com

Introduction: Bulk-heterojunction cells – a solution to low costs



Konarka®

Capacity Upscaling

Lab

2006
5 cm
1kWatt

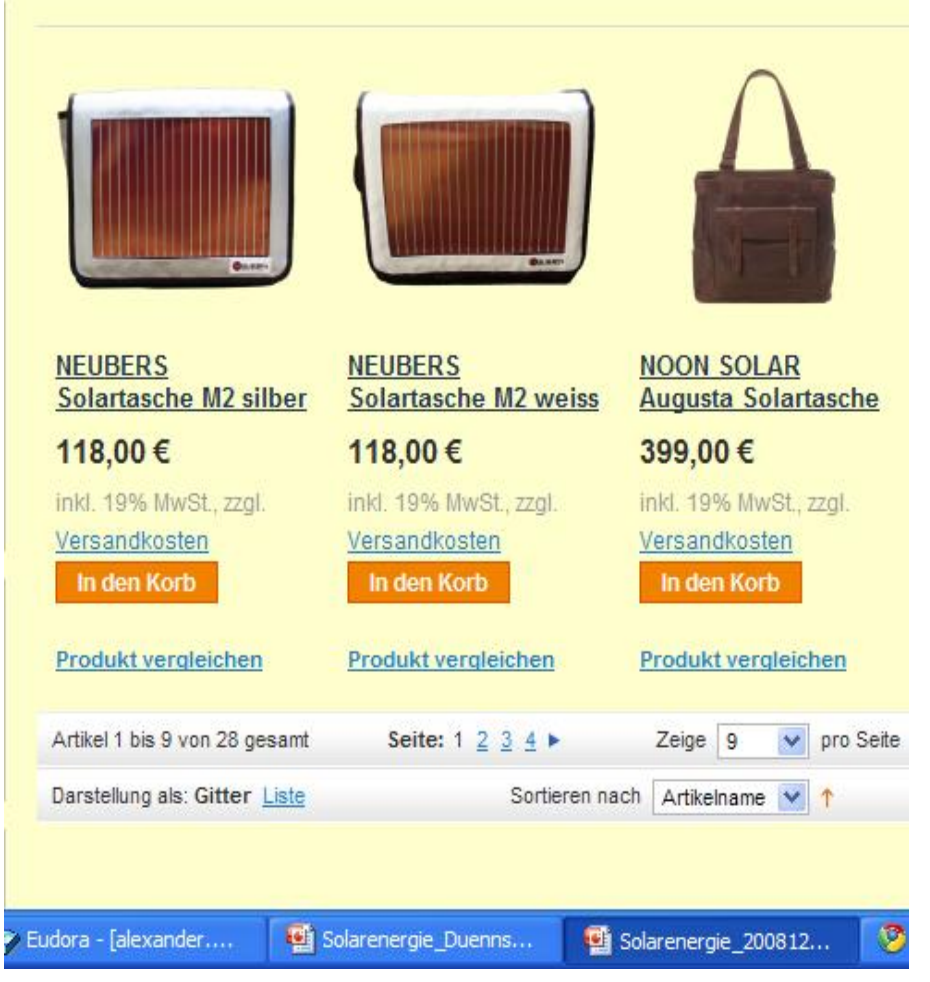
Pilot

2007
25 cm
1MWatt

Production

2008
150 cm
1GWatt

The first Konarka product (2009)



www.solarbag-shop.de

KONARKA®

Konarka Technologies Files for Chapter 7 Bankruptcy Protection

Lowell, Mass. - June 1, 2012 - Konarka Technologies, Inc., a leading developer of thin-film solar panels, has filed for bankruptcy protection under chapter 7 of the Federal bankruptcy laws. Under chapter 7 proceedings, the company's operations cease and a trustee is tasked with liquidating the company's assets for the benefit of creditors. Creditors will be asked to submit their claims to the Bankruptcy Court and are unable to obtain payment from the company.

Howard Berke, chairman, president and CEO of Konarka, said, "Konarka has been unable to obtain additional financing, and given its current financial condition, it is unable to continue operations. This is a tragedy for Konarka's shareholders and employees and for the development of alternative energy in the United States."

Konarka was founded by Mr. Berke and by Dr. Alan Heeger, the winner of the Nobel Prize for his work in conductive polymers. Among the Company's assets are over hundreds of owned and licensed patents and patent applications in the field of solar energy and a state-of-the-art manufacturing plant in New Bedford, Massachusetts.

Mr. Berke noted that several large international companies had expressed interest in financing or acquiring the company. He further noted that, given the worldwide interest in the company, including from the Chinese government, the company had not entirely given up hope that a rescue financing or acquisition would emerge in the bankruptcy. Under Chapter 7 proceedings, however, any such transactions are evaluated by a trustee and not by the company itself.

Further information about the company, including a copy of its petition in bankruptcy, is contained on Konarka's website, http://www.konarka.com.

#

Belectric acquires Konarka Technologies

By Syanne Olson | Oct 22, 2012 10:47 PM BST | 0

Share

Belectric advised that the deal to acquire Konarka Technologies has been completed, with an agreement reached between the two companies. Konarka Technologies applied for insolvency earlier this year and began negotiations with several investors. Alexander Kubusch, preliminary insolvency administrator from Curator, commented, "…our talks have now reached a successful conclusion. Of the many interested parties, we ultimately opted for Belectric Holding, because this company not only offered an ideal solution to the issue of business operations but also went a long way toward upholding the interests of creditors."

Konarka Technologies will now operate as Belectric OPV and have its whole team, led by former Director of European Operations and current CEO Ralph Pätzold at the company's Nürnberg site. The company will continue research, development and production, as well as international distribution of its printed PV cells. Over the coming year, Belectric OPV will look to increase the service life of the organic solar cells, performing different tests over the first phase.

Michael Belschak, CFO of Beletric Holding, expects the first revenue to be generated as early as the second half of 2013. Belschak commented, "We will use Power Plastic wherever conventional modules aren't a suitable solution. Particularly in facade construction and in the automotive sector, the highly flexible and pliable material can be used in a variety of ways to save energy cost-effectively. And we have already received some inquiries from the consumer segment, where there is also great interest in the product."

SOLARTE. powered by BELECTRIC®

MERCK

Press Release

Thursday, November 26th 2015

Gray Modules: New Dimension in Organic Photovoltaics for Buildings

Merck´s new lisicon formulation enables greater power generation of more than 50 W/m² in semi-transparent Belectric OPV modules

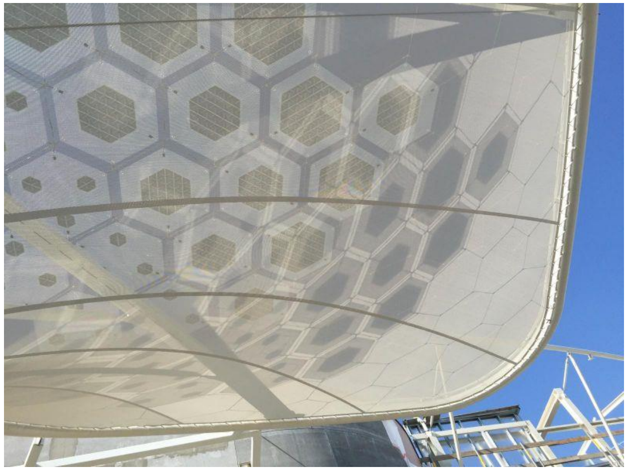
Darmstadt and Nuremberg, Germany, November 26, 2015 – Merck, a leading science and technology company, announced that semi-transparent gray-colored organic photovoltaic (OPV) modules are now available on the market. The new materials, which were successfully developed together with Belectric OPV, were recently presented to the public at the Adaptive Architectures and Smart Materials Conference in Chicago. The showpiece, using gray freeform modules, comprises several laminated glass panes mounted with steel ropes to create a lightweight, curtain-wall-type façade. This offers unlimited design options for modern architectural accents while maintaining transparency and shape.

The modules include Merck's new lisicon formulation, which achieves superior performance by enabling greater than 50 W/m² power generation in the Belectric OPV modules while remaining semi-transparent. They were optimized and produced in a large-scale production set-up and are ready for commercialization. Merck and Belectric OPV have previously presented the lively blue-colored OPV, which was already used in the installations at the EXPO 2015 at the German Pavilion in Milan, Italy and in the headquarters building of the African Union Security and Peace Council in Addis Ababa, Ethiopia.

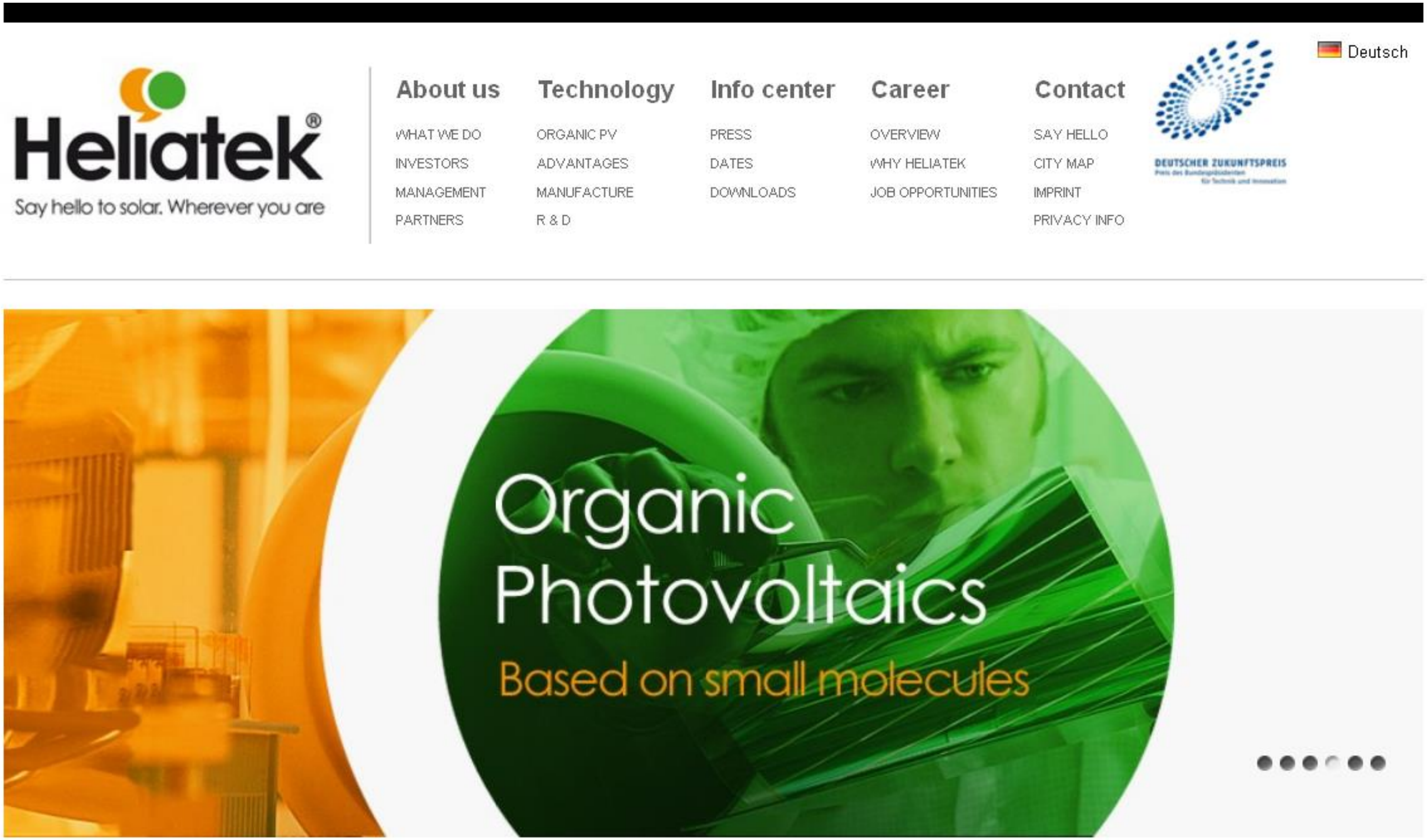
There are many important advantages of OPV technology, especially with respect to building-integrated photovoltaics (BIPV). OPV modules do not show the performance drop usually observed with traditional inorganic photovoltaics in diffuse lighting conditions and under elevated temperatures – typical conditions found in façades. In addition, semi-transparency and tunable colors as well as freedom of design in shape and form are attractive and often even essential features for BIPV applications.

Brian Daniels, Head of the Advanced Technologies business unit at Merck, says, "From many architects we have learned that a gray color will significantly increase the usage of OPV in building integration. Following the installations at the Expo in Milan, we set an aggressive target to develop such a solution. Achieving the intended color with our partner Belectric OPV in such a short time while also achieving superior performance clearly demonstrates the momentum we are gaining within the OPV industry." Ralph Pätzold, CEO of Belectric OPV added, "The new gray is a key for the wider adoption of OPV. We are very proud that – in the joint effort with Merck – we could bring the new material to a manufacturing quality in very short time. Now all our partners in the construction material segments can benefit instantly from the new color tone."

Buildings account for 40% of energy consumption and 36% of CO_2 emissions in the EU. As a consequence, the EU has set a target for all new buildings to be nearly zero-energy (NZEB) as of 2021. The achievement of the legally binding NZEB objectives will require active building envelopes since passive materials are reaching their own limits. Gray OPV-based active building elements are an important step forward to combine energy generation and the aesthetic needs of architects.



www.solarte.de



www.heliatek.de

Heliatek®

Say hello to solar. Wherever you are

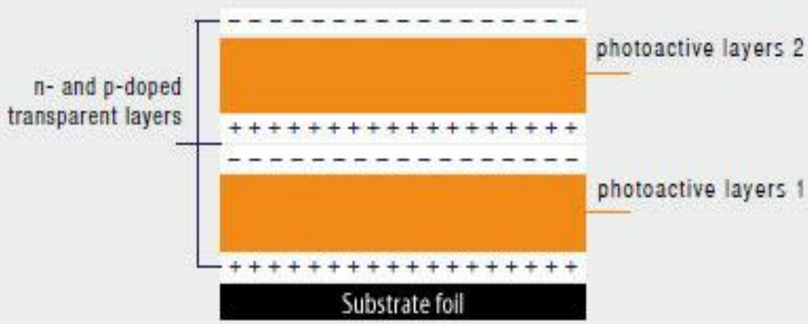
Heliatek sets new world record efficiency of 10.7% for its organic tandem cell

April 27, 2012

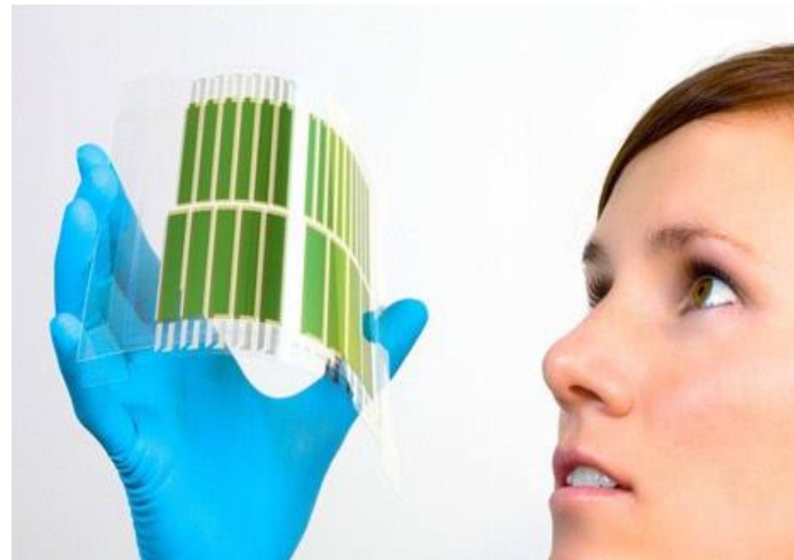
Heliatek GmbH, technology leader in the field of organic solar films, continues to set new world records for organic solar cells. The company has commissioned SGS, an accredited and independent testing facility, with a measurement campaign of its latest organic photovoltaic (OPV) cells. The result of this campaign is a new world record for OPV with 10.7 % cell efficiency on 1.1 cm2. It also confirms the superior low light and high temperature performances of OPV compared to traditional solar technologies.

Heliatek‘s Technology

Build of a tandem cell



- patented tandem cell technology
- complementary absorber systems
  > optimum harvesting of the complete sun spectrum
- increased open circuit voltage
- loss-free recombination contact between individual cells within tandem cell
- n- and p-doped transparent layers allow for the loss-free charge transport to the electrodes.



Part of the solution to both the worlds energy and environmental issues

Affordable energy for emerging nations

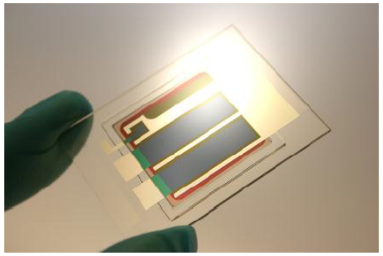
Light-weight, flexible energy on the move

Heliatek®

Say hello to solar. Wherever you are

Heliatek consolidates its technology leadership by establishing a new world record for organic solar technology with a cell efficiency of 12%

Dresden, Germany, January 16, 2013 – Heliatek GmbH, the leader in organic solar films, today announced a record breaking 12.0% cell efficiency for its organic solar cells. This world record, established in cooperation with the University of Ulm and TU Dresden, was measured by the accredited testing facility SGS. The measurement campaign at SGS also validated the superior low light and high temperature performances of organic photovoltaics (OPV) compared to traditional solar technologies.



Heliatek world record cells with 12.0% efficiency on an active area of 1.1 cm².

The 12.0% record cell on a standard size of 1.1 cm² combines two patented absorber materials, which convert light of different wavelengths. Using two different absorber materials creates a stronger absorption of photons and improves energetic utilization through a higher photovoltage. Thanks to OPV's unique behavior at high temperatures and low light conditions, this 12% efficiency is comparable to about 14% to 15% efficiency for traditional solar technologies like crystalline silicon and thin film PV. Whereas those technologies significantly lose cell efficiency with rising temperatures and decreasing solar irradiation, organic cells increase their efficiency in these conditions leading to a much higher energy harvesting in real life environments.

Heliatek®

The future is light

Heliatek sets new Organic Photovoltaic world record efficiency of 13.2%

Dresden, Germany - 8 February 2016 - Heliatek R&D teams reached a record conversion efficiency of 13.2% for an OPV multi-junction cell, setting a new world record for the direct conversion of sunlight into electricity using organic photovoltaic cells. The measurement was independently confirmed by Fraunhofer CSP.

Thanks to the excellent low light and high temperature behavior of the organic semiconductor, the electricity generation of the newly developed cells corresponds to the output of conventional solar cells with 16 to 17% efficiency when both are under real world conditions.

Heliafilm® - superior low light and high temperature energy harvesting performance.

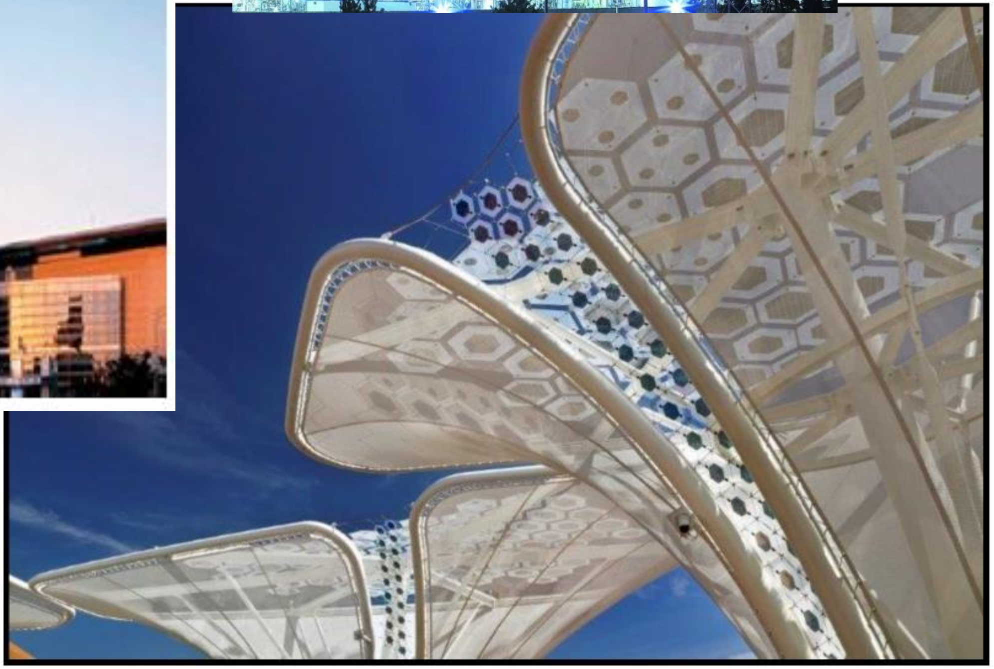
This new result confirms the world-leading technology position of Heliatek as demonstrated by its continuous progress from 3% to more than 13% efficiency over the last 10 years. It also supports its roadmap towards 15% efficient organic solar cells. The result further validates Heliatek's unique technology approach of using vacuum deposition of small molecules on plastic films.

RESS RELEASE

Feb 08, 2016

Energy harvesting for sensor networks

Building integration



Mechanical flexibility

Outline

6.8 Organic and Perovskite Solar Cells

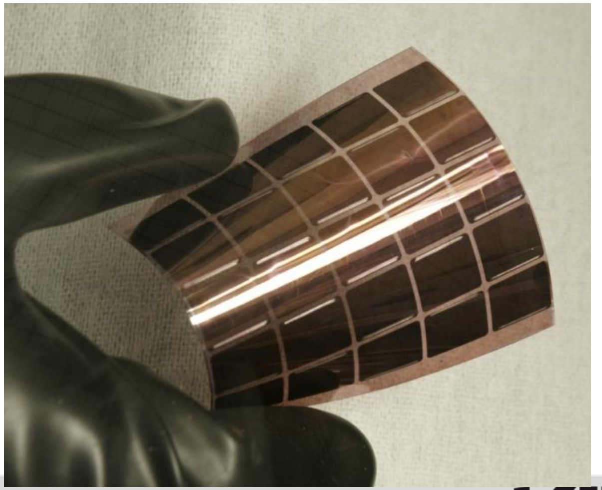
6.8.1 Organic Semiconductors

6.8.2 Low Bandgap Materials

6.8.3 Semitransparent and Tandem Solar Cells

6.8.4 OPV Industry

6.8.5 Perovskite Solar Cells



Sequential deposition as a route to high-performance perovskite-sensitized solar cells

Julian Burschka[1]*, Norman Pellet[1,2]*, Soo-Jin Moon[1], Robin Humphry-Baker[1], Peng Gao[1], Mohammad K. Nazeeruddin[1] & Michael Grätzel[1]

- start with TiO_2-layer (via spray pyrolysis)
- spin coat PbI_2 from solution
- dip into CH_3NH_3I in 2-propanol
- $CH_3NH_3PbI_3$ perovskite crystals are formed
- spin coat hole transport layer on top

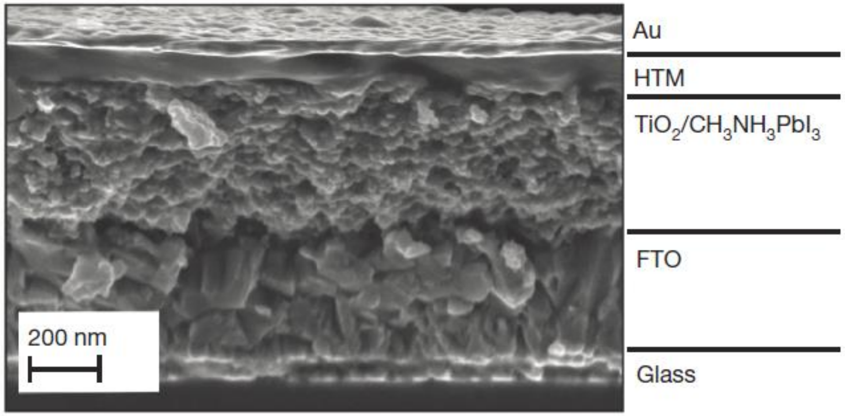
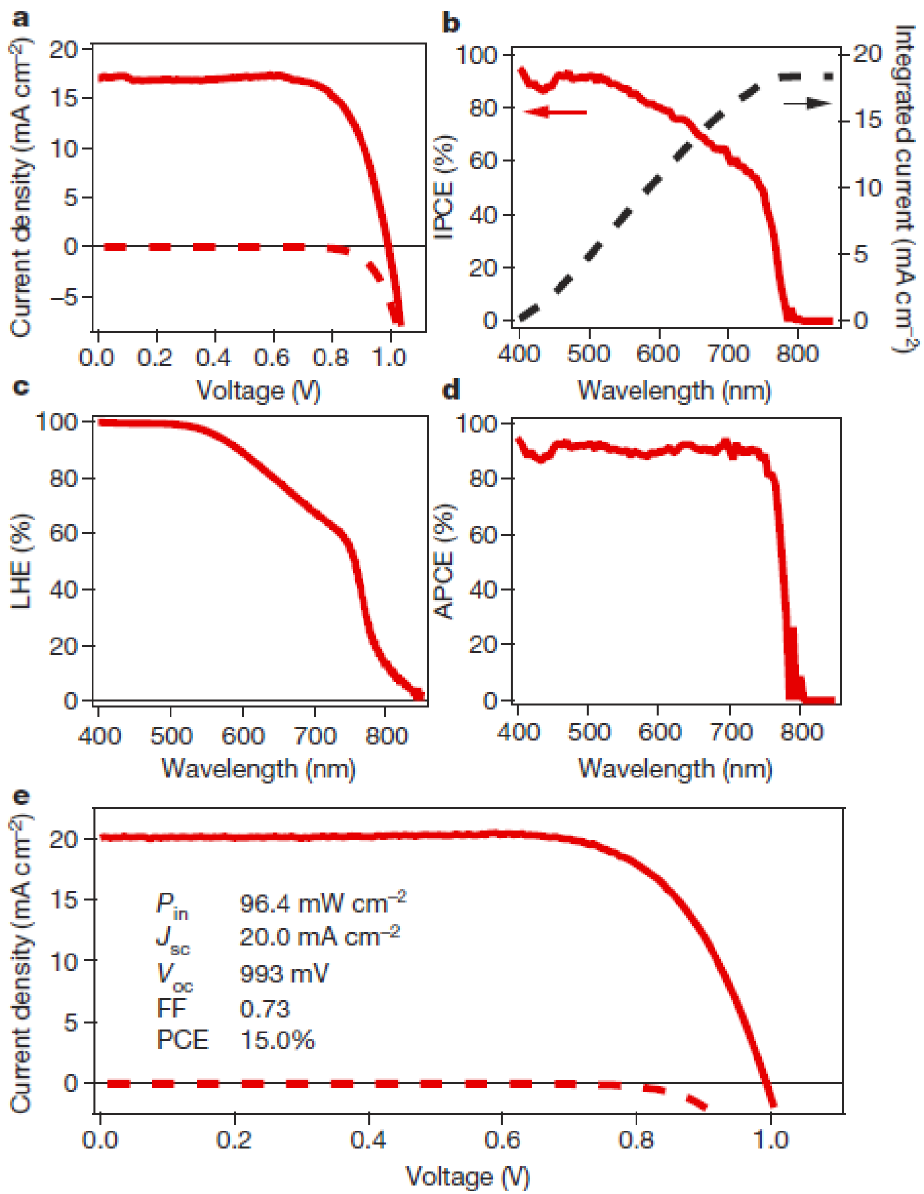


Figure 2 | Cross-sectional SEM of a complete photovoltaic device. Note that the thin TiO_2 compact layer present between the FTO and the mesoscopic composite is not resolved in the SEM image.

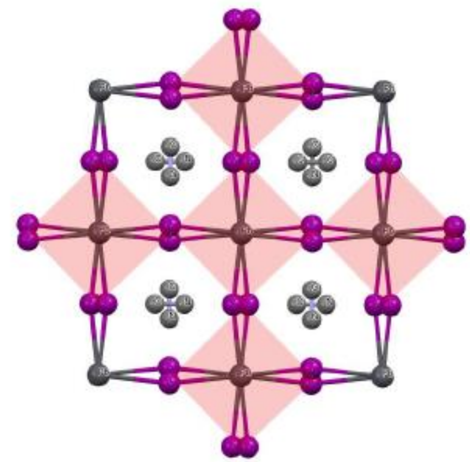
00 MONTH 2013 | VOL 000 | NATURE | 1

Received 3 April; accepted 29 May 2013.
Published online 10 July 2013.

Karlsruhe Institute of Technology



$CH_3NH_3PbI_3$



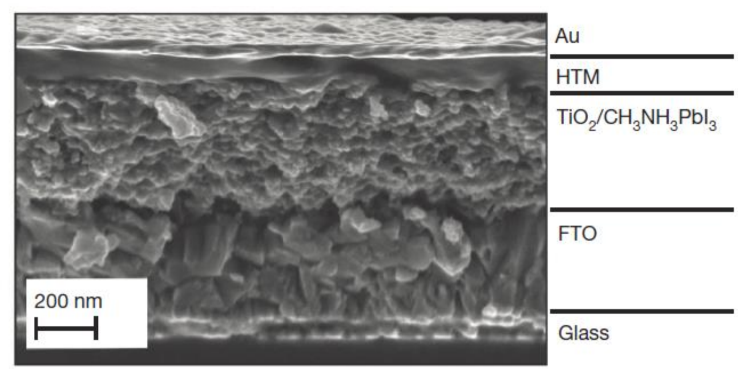
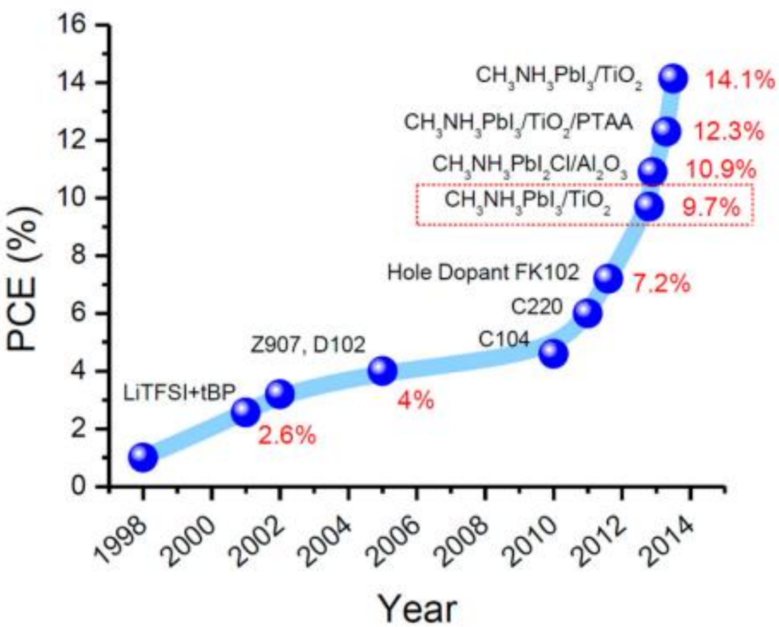
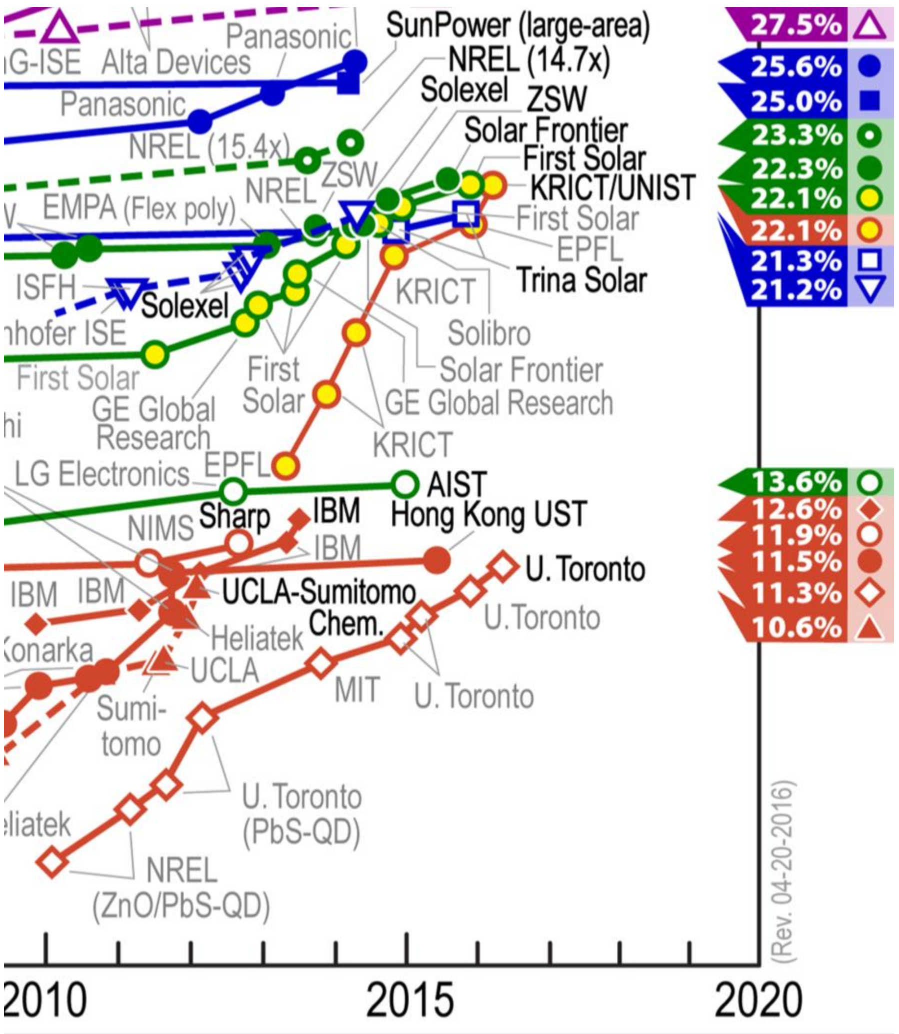


Figure 2 | Cross-sectional SEM of a complete photovoltaic device. Note that the thin TiO_2 compact layer present between the FTO and the mesoscopic composite is not resolved in the SEM image.





Karlsruhe Institute of Technology