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Workshop on Nanoscience for Solar Energy Conversion

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Toward High Performance Plastic Solar Cells: Basics and Recent Developments

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Toward high performance plastic solar cells: basics and recent developments

Nadia Camaioni

Consiglio Nazionale delle Ricerche

Istituto per la Sintesi Organica e la Fotoreattività (ISOF)

Bologna (Italy)

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.

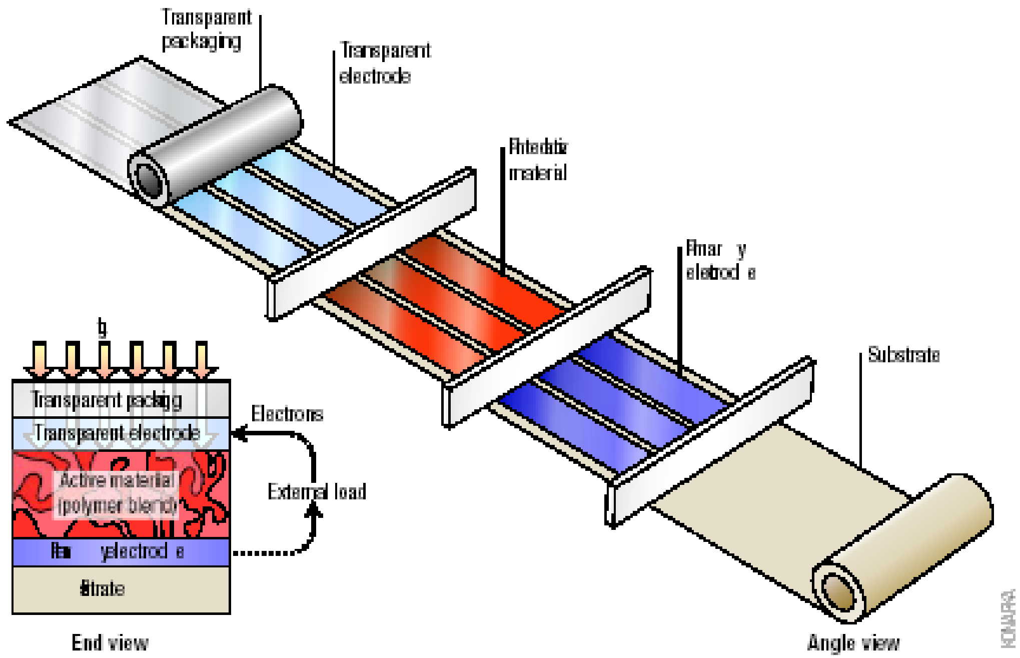


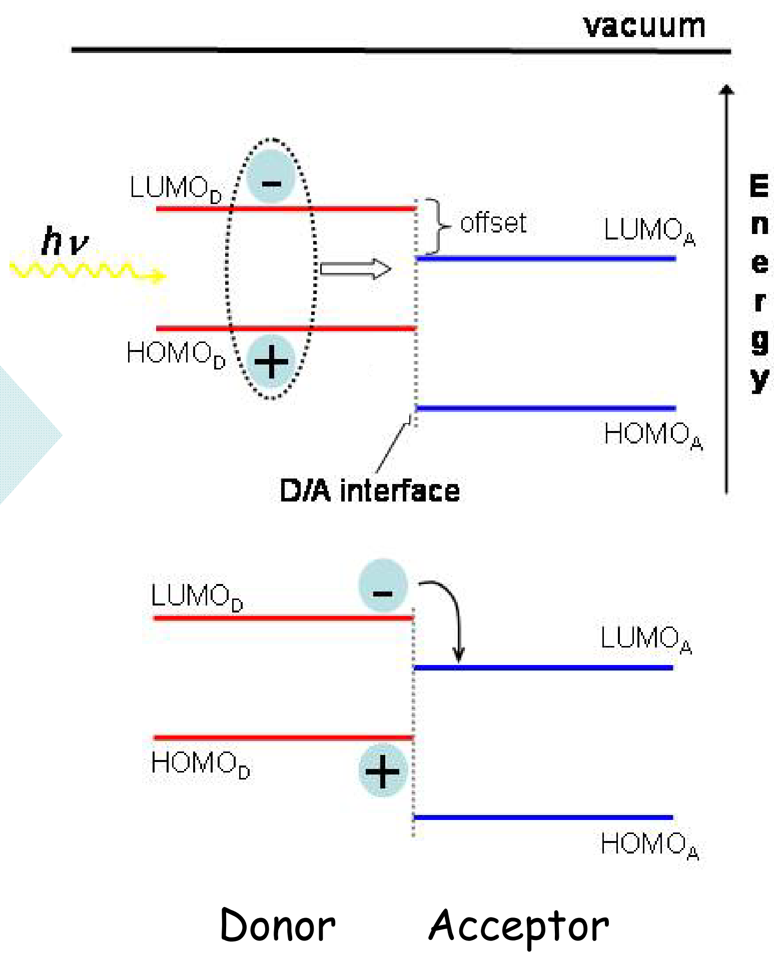
Figure 1 Polymer-based photovoltaic cells can be manufactured using standard printing processes.

KONARKA®

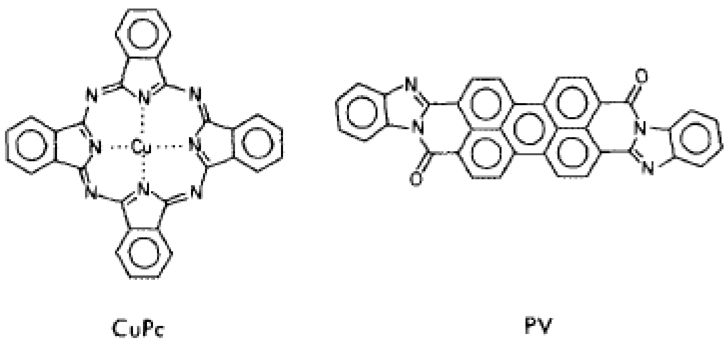
Electron-donor (D) and electron-acceptor (A) materials

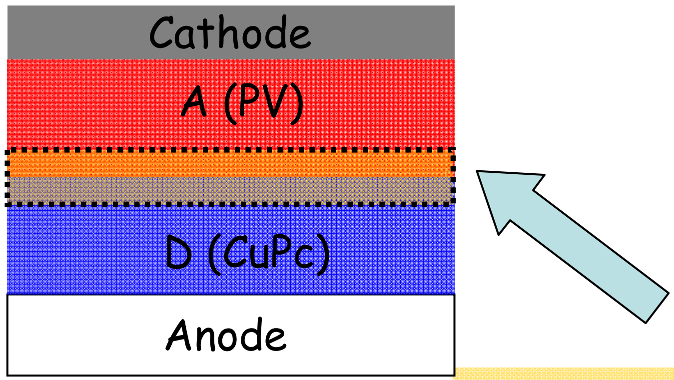
Fundamental steps of the photovoltaic process in excitonic solar cells:

- ❑ Absorption of light and generation of excitons
- ❑ Diffusion of excitons and their dissociation with generation of free charge carriers
- ❑ Transport and collection of charge carriers



Tang's cell: the bilayer approach





limited photoactive region!

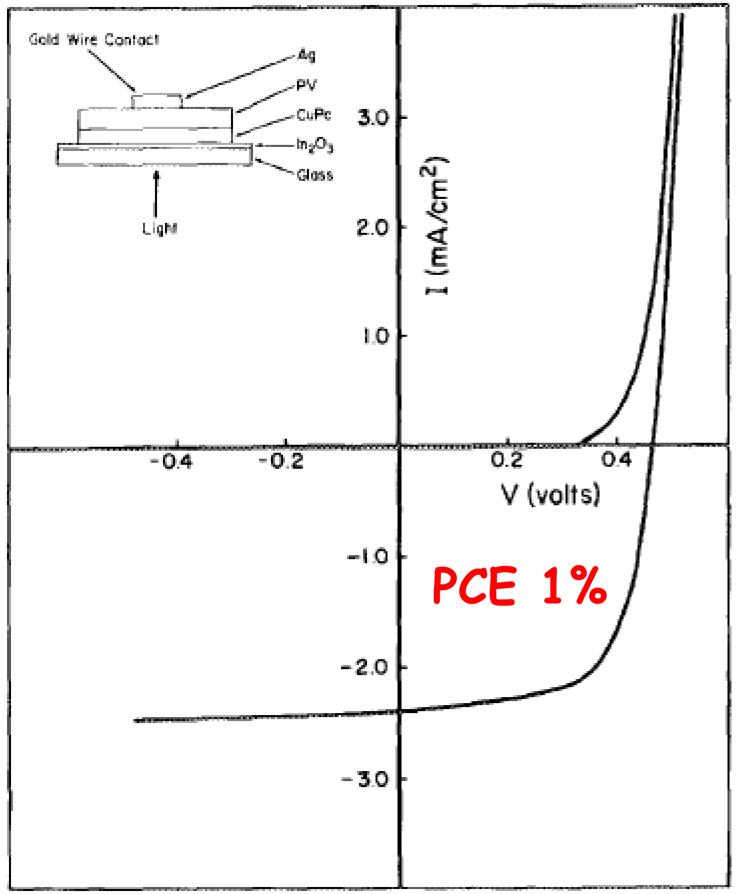
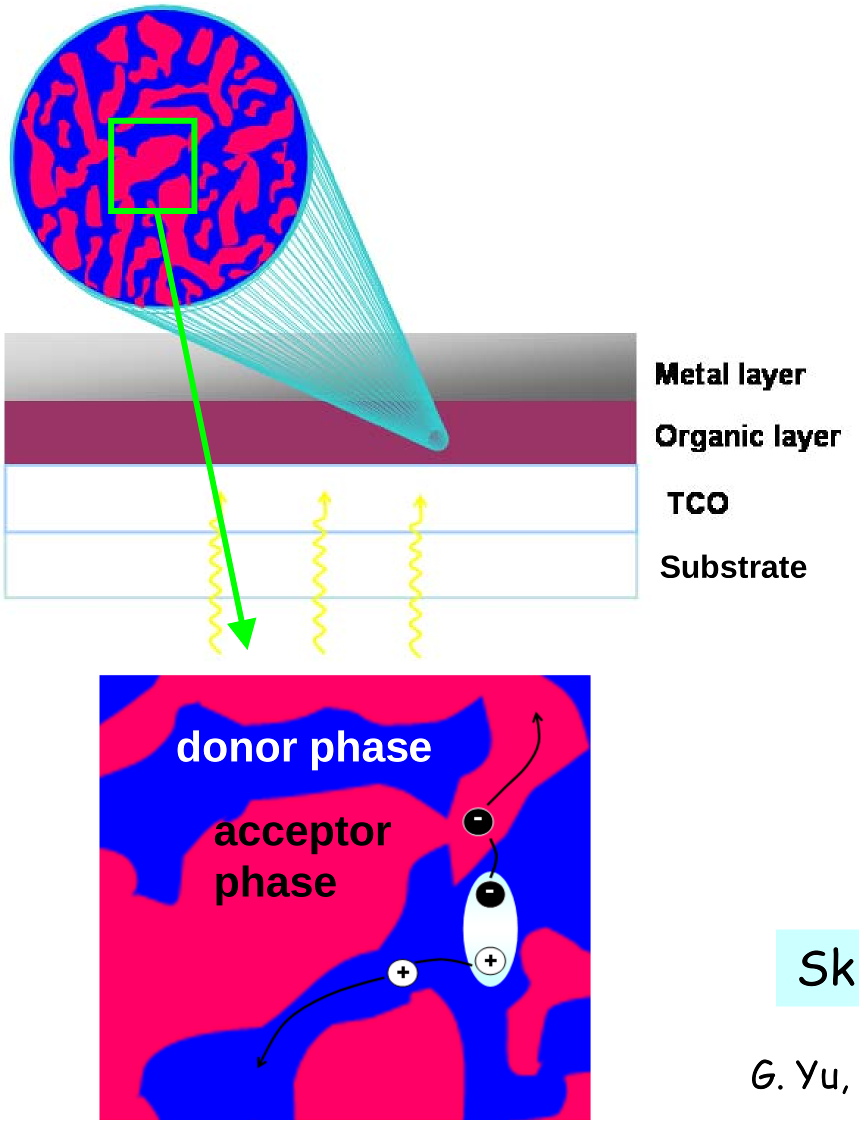


FIG. 1. Configuration and current-voltage characteristics of an ITO/CuPc (250 Å)/PV(450 Å)/Ag cell.

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

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

The bulk-herojunction (BHJ) approach: the bicontinuous D/A active layer

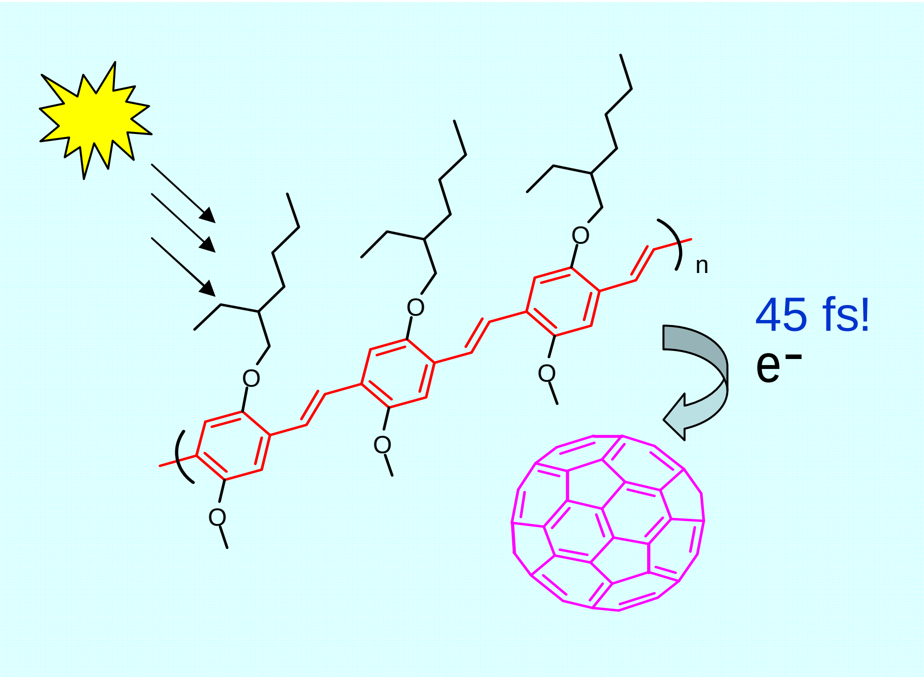


- ❑ Donor and acceptor materials are mixed together on the <u>nanoscale level</u>. Both materials must be very soluble in the same solvent!
- ❑ All photogenerated excitons are within a diffusion length (10-20 nm) of a D/A interface
- ❑ Distributed <u>active interfaces throughout the bulk of the device</u>
- ❑ <u>Percolation limit</u> for both materials has to be reached. The blend morphology has to enable charge-carrier transport in the <u>two different phases</u> in order to minimize recombination

Skill lies in controlling the nanomorphology!

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

Conjugated polymers - Fullerene: excellent donor-acceptor pairs



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

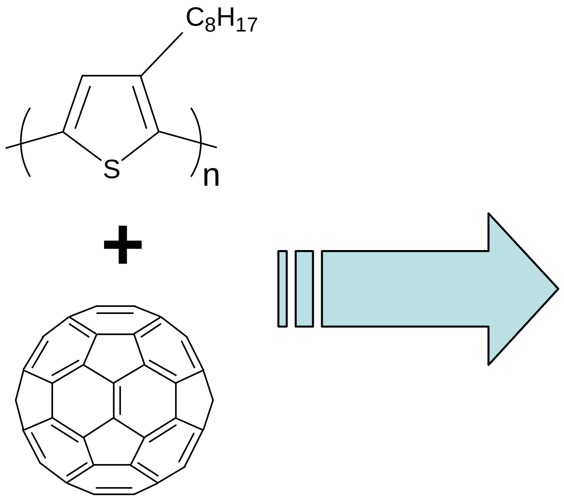
<u>Every photon absorbed yields one pair of separated charges!</u>

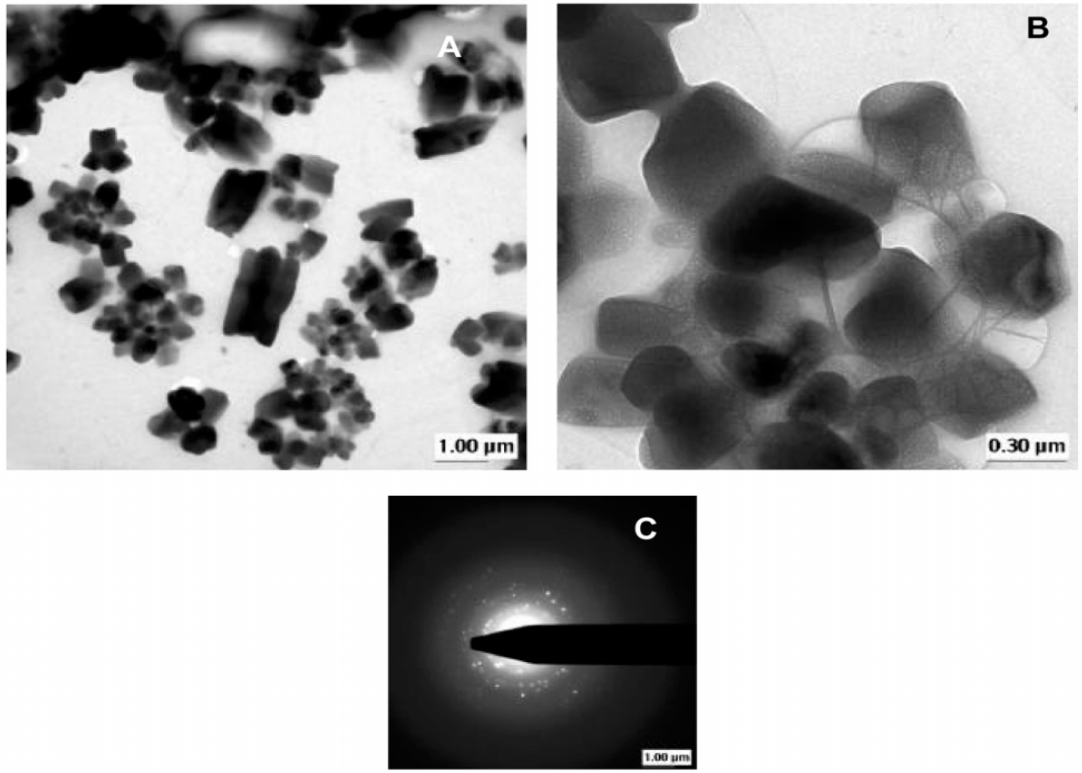
Quantum efficiency for charge separation approaches unity

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

Soluble fullerene derivatives are required

P3OT:C60 (1:1 by wt.)





N. Camaioni et al., *Thin Solid Films 403* (2002) 489

Common soluble derivatives of fullerene

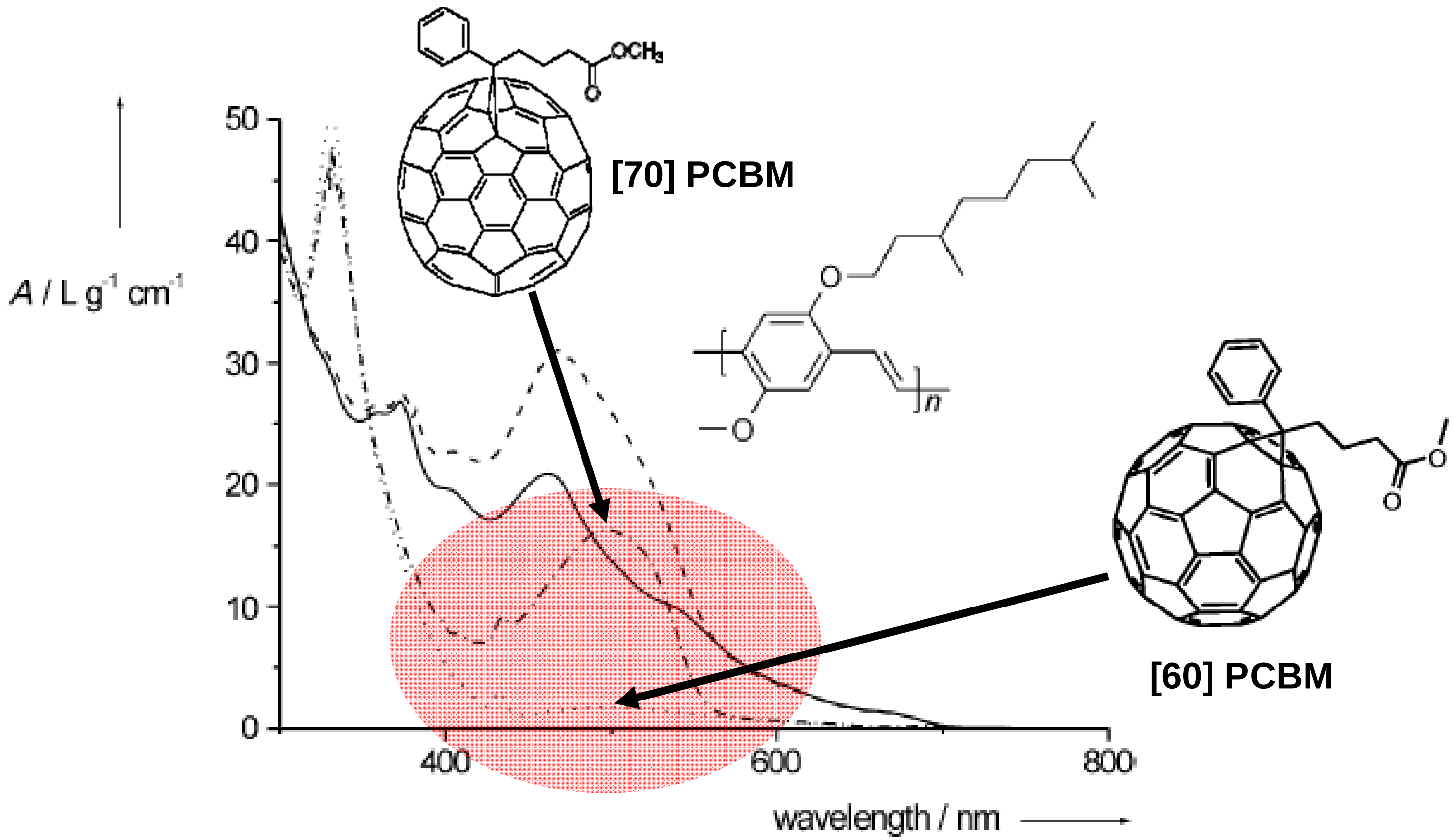


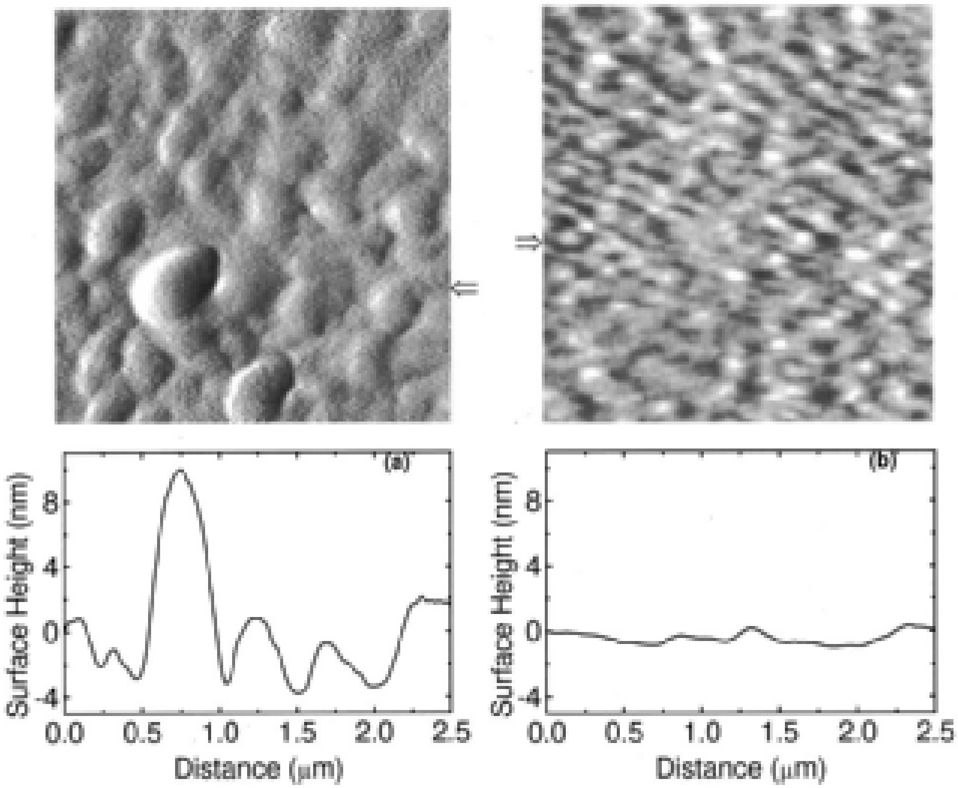
Figure 1. UV/Vis spectra of [70]PCBM (——) and [60]PCBM (•••••), both in toluene. To illustrate the contribution of MDMO-PPV to the absorption, the (normalized) spectra of [70]PCBM:MDMO-PPV (4:1, w/w; -----) and [60]PCBM:MDMO-PPV (4:1, w/w; –•–•), also in toluene, are also represented. The inset shows the structure of MDMO-PPV.

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

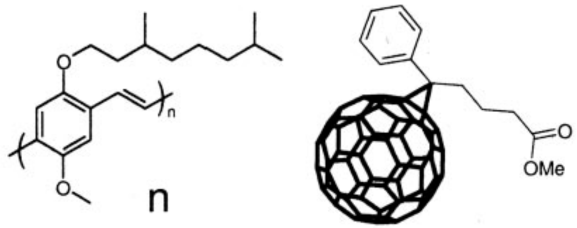
The role of morphology in BHJ solar cells

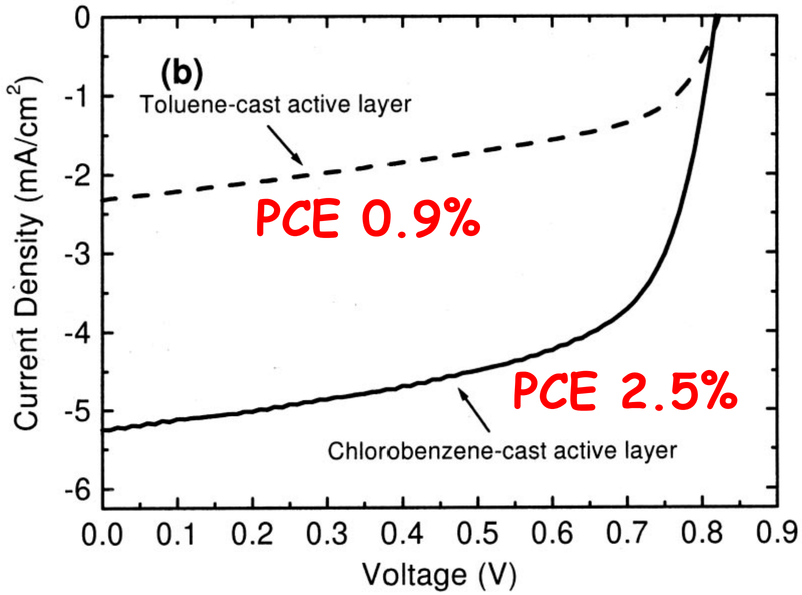
MDMO-PV:PCBM 1:4 by wt.

Toluene-cast Chlorobenzene-cast



MDMO-PPV PCBM



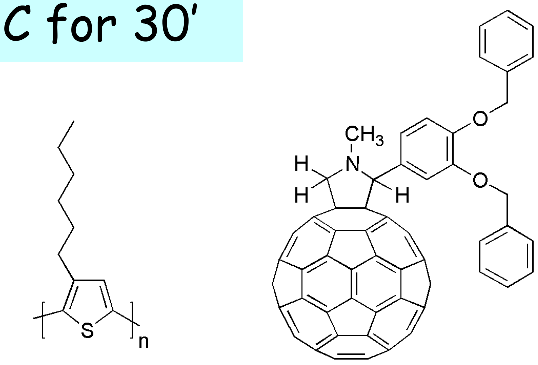


S.E. Shaheen et al., *Appl. Phys. Lett. 78*, (2001) 841

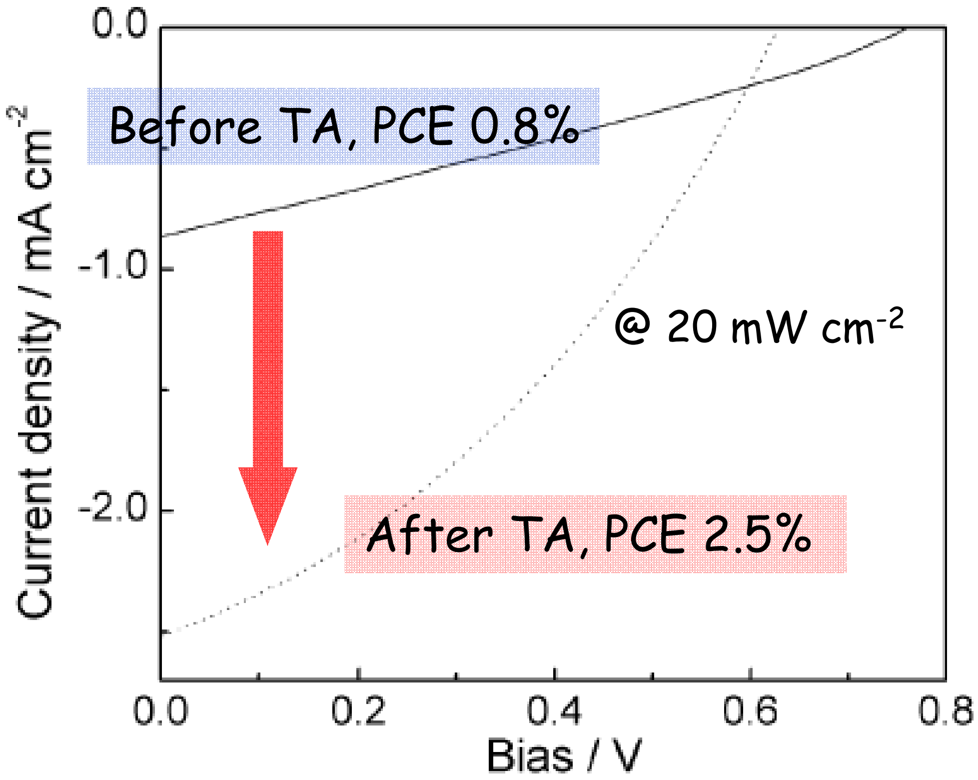
Morphology control with thermal annealing

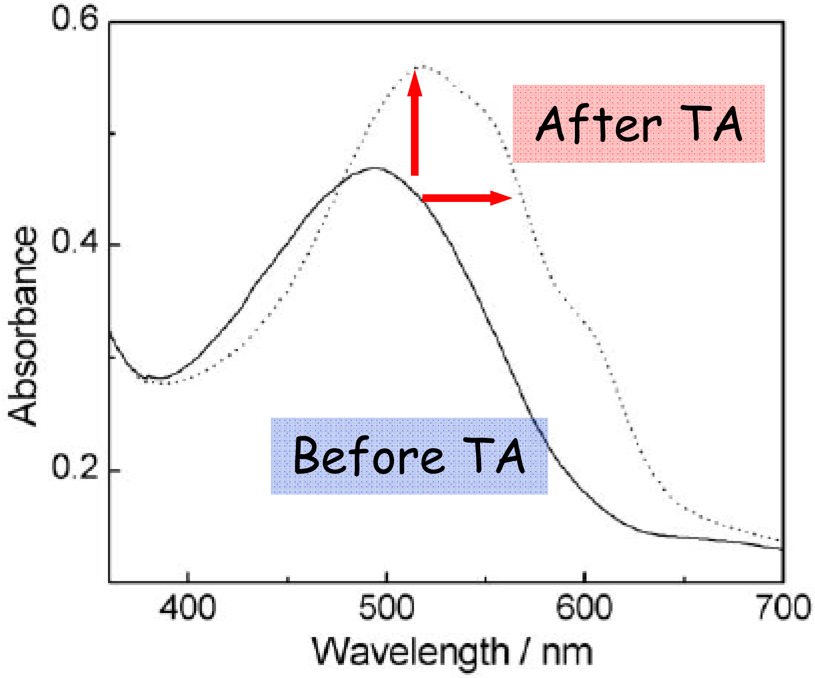
Thermal annealing (TA) @ 55 °C for 30′

P3HT:PFPYE 3:2 by wt.



P3HT FPYE

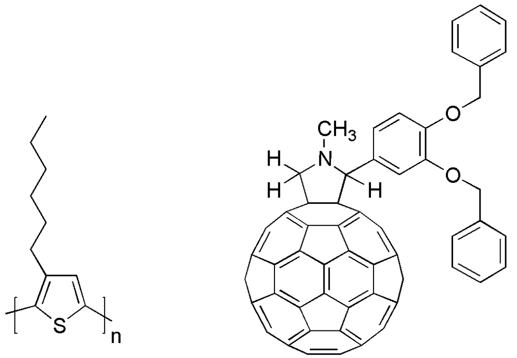




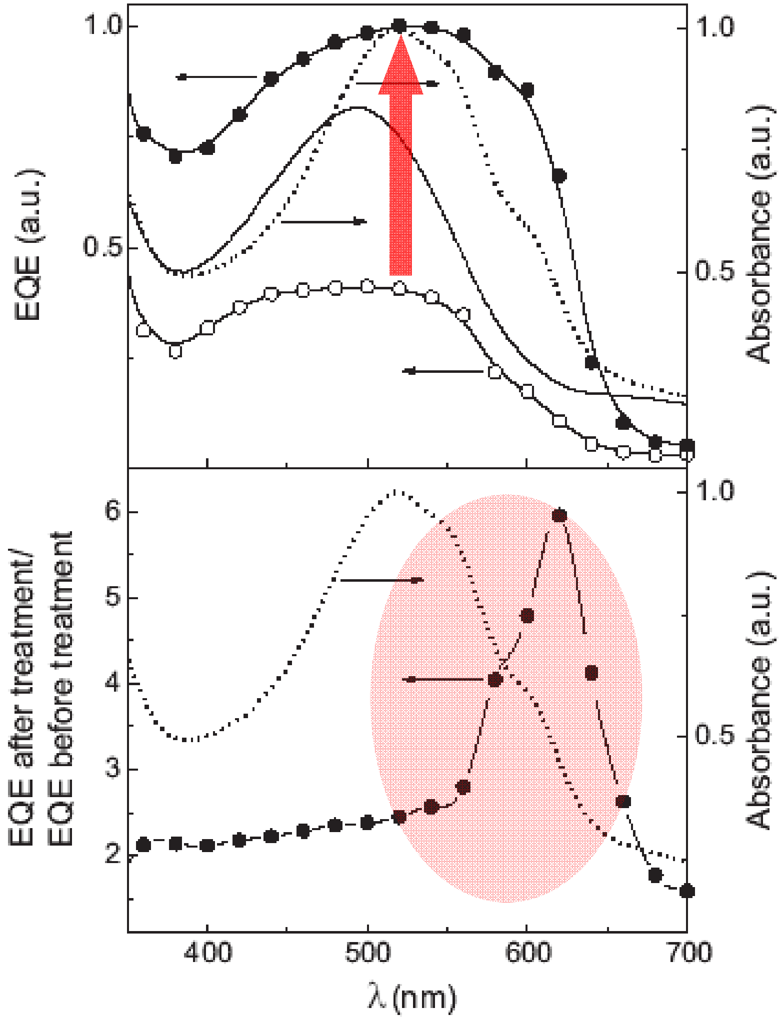
N. Camaioni, et al., *J. Mater. Chem.*, *12*, (2002) 2065

Thermal annealing (TA) @ 55 °C for 30′

P3HT:PFPYE 3:2 by wt.



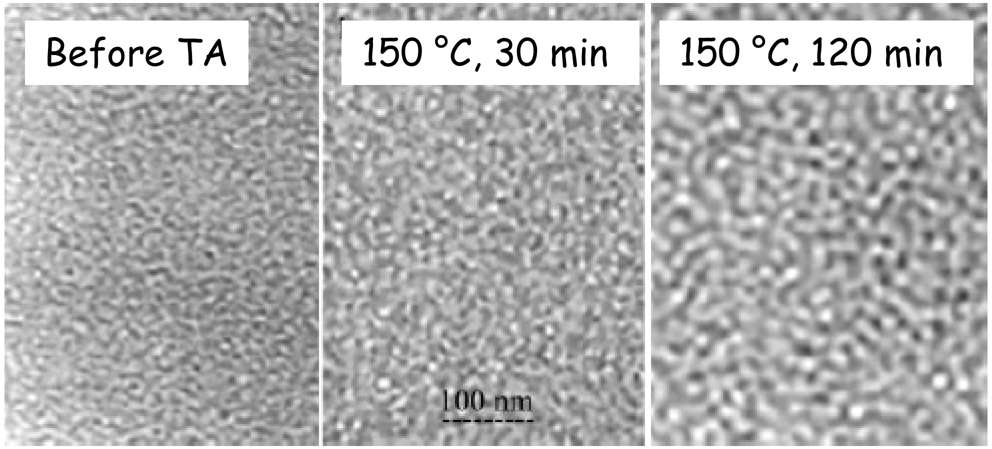
P3HT FPYE

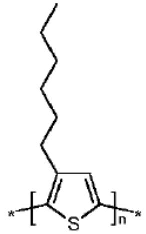


N. Camaioni, et al., *Adv. Mater., 14*, (2002) 1735

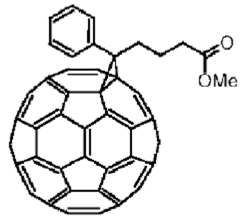
Thermal annealing (TA) @ 150 °C for 30′

P3HT:PCBM 1.0:0.8 by wt.

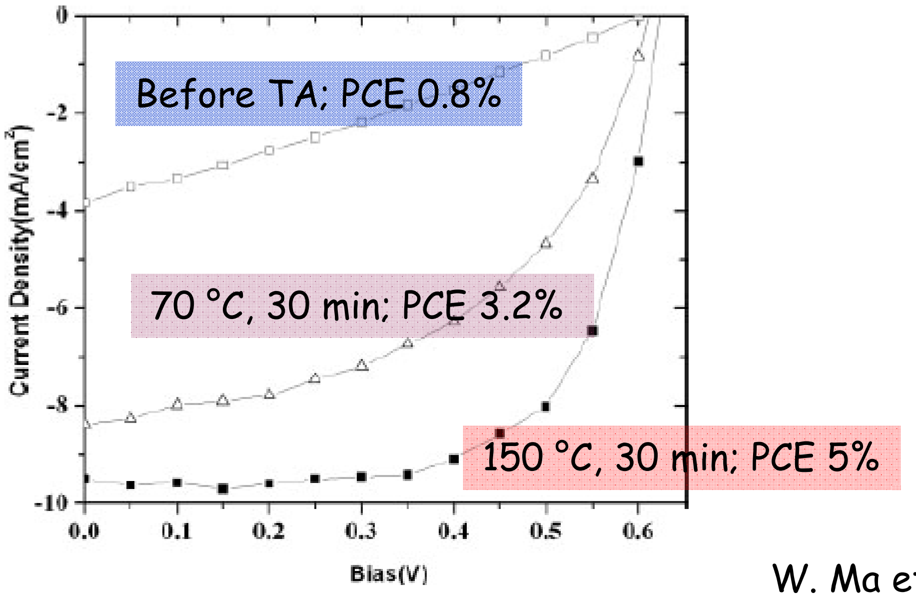


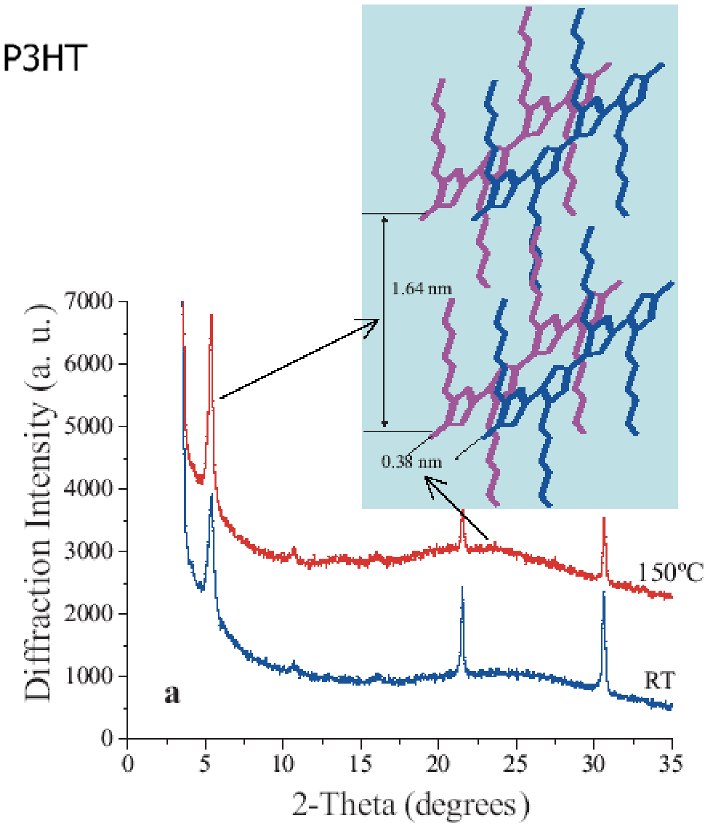


P3HT



PCBM

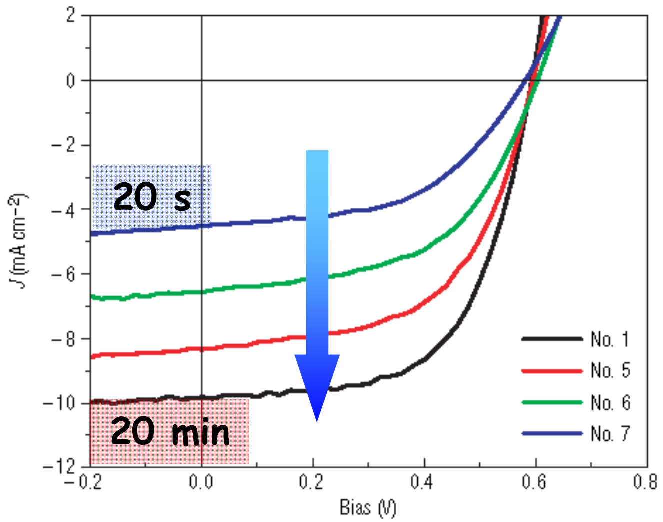


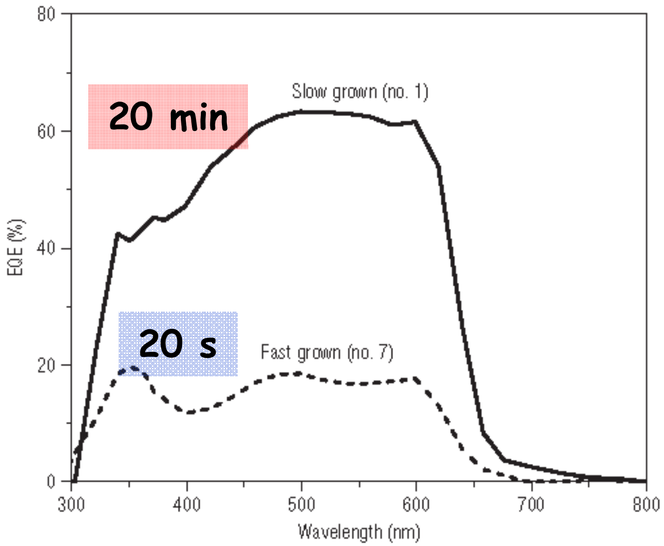


W. Ma et al., *Adv. Funct. Mater.* *15* (2005) 1617

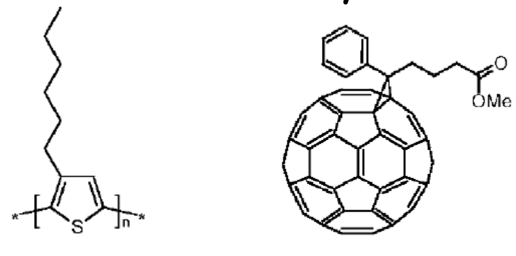
Morphology control vith “solvent-annealing”

DCB evaporation time



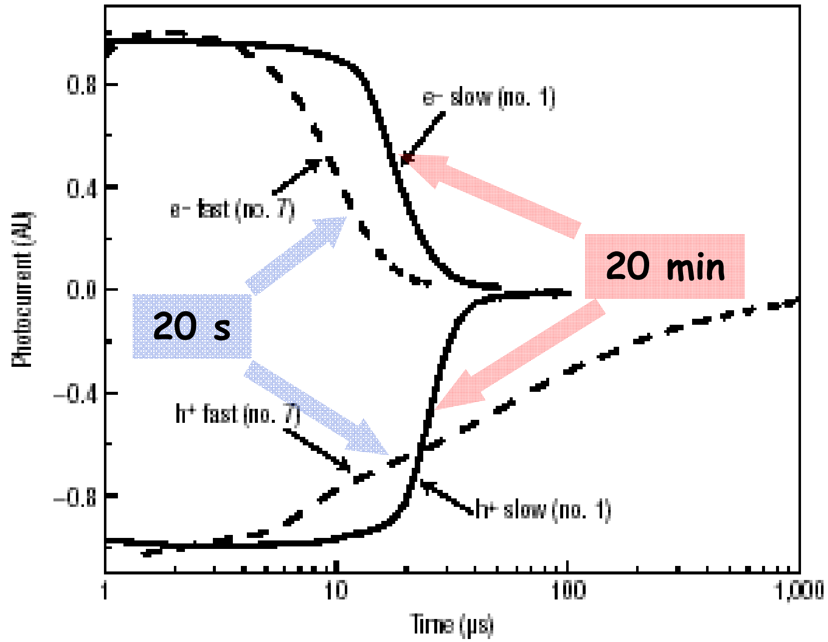


P3HT:PCBM 1:1 by wt.



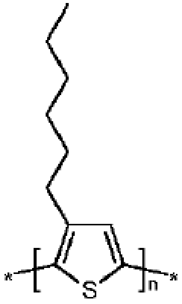
P3HT

PCBM

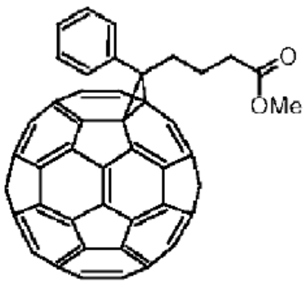


G. Li et al., *Nature Mater. 4*, (2005) 864

Current state of the art



P3HT



PCBM

Power conversion efficiencies between 5% and 6%
5% certified by NREL

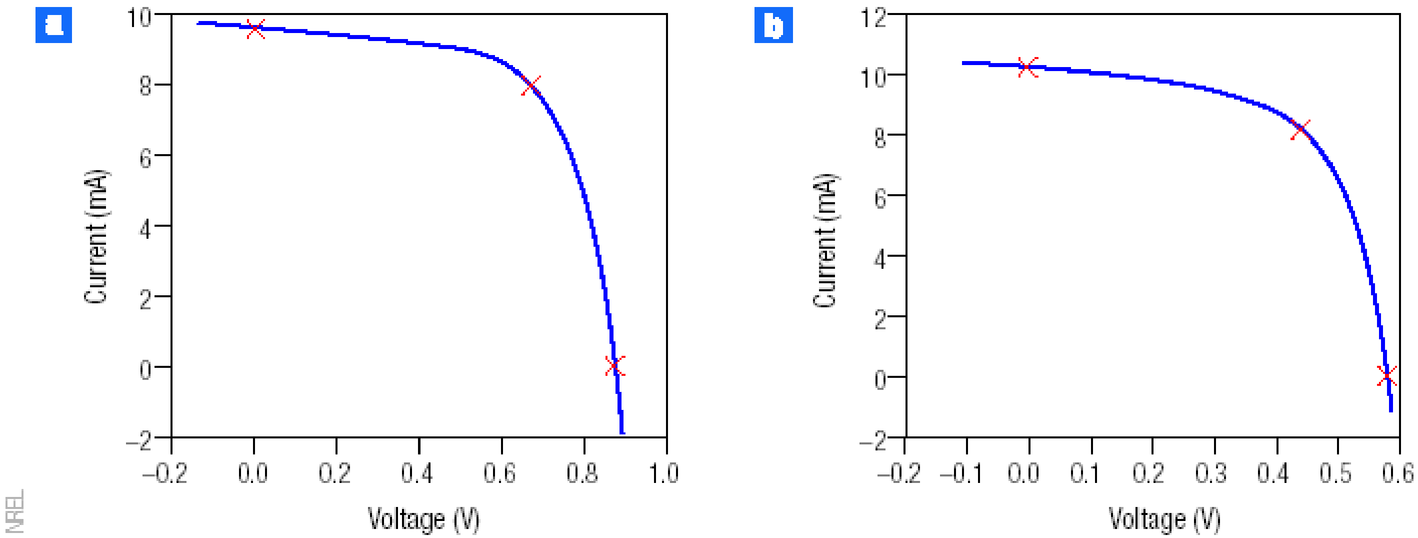
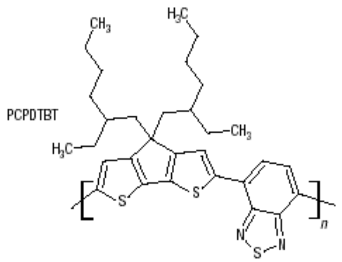


Figure 2 These plots show record efficiencies achieved with organic photovoltaic technology as certified by the National Renewable Energy Lab (NREL). **a**, Results for a device with an active area of 1.024 cm^2 and an efficiency of 5.21%. **b**, Results for a device with an active area of 0.685 cm^2 and an efficiency of 5.24%.

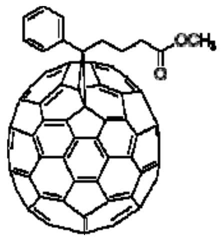
R. Gaudiana et al., *Nature Photonics 2* (2008) 287

Morphology control with "additives"

Additives: alkanedithiols with different chain lengths (2.5% in volume)



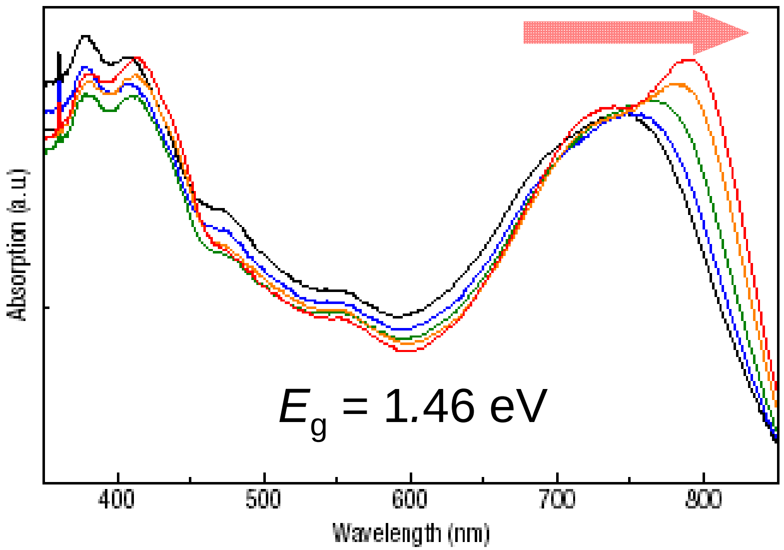
PCPDTBT



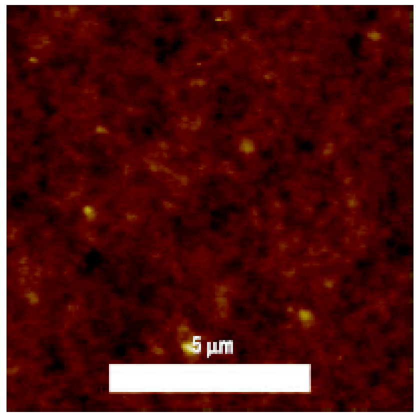
[70]PCBM

PCPDTBT:[70]PCBM films cast from chlorobenzene containing:

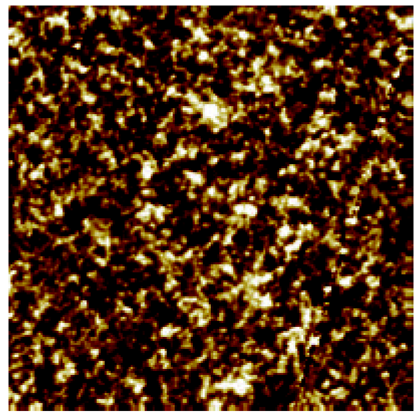
- no dithiol (black)
- 1,4-butanedithiol (green)
- 1,6-hexanedithiol (orange)
- 1,8-octanedithiol (red)



no alkanedithiols

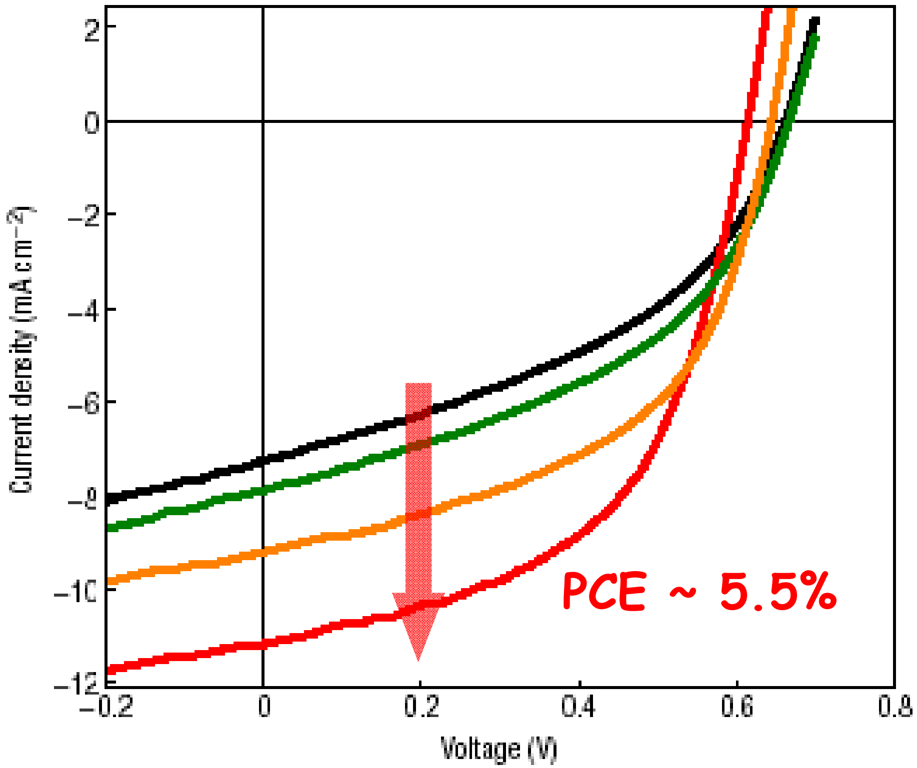


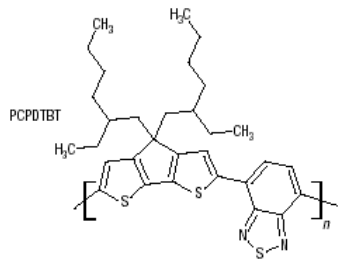
1,8-octanedithiol



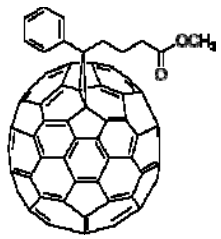
J. Peet et al., *Nature Mater. 6*, (2007) 497

Additives: alkanedithiols with different chain lengths (2.5% in volume)





PCPDTBT



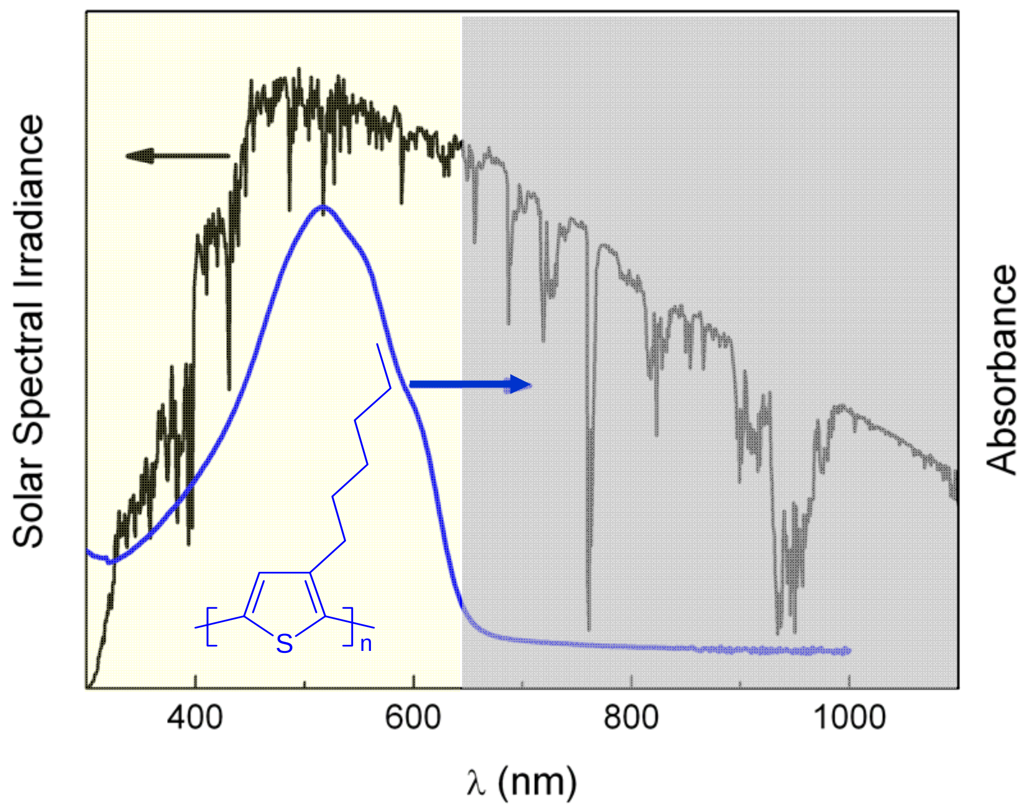
[70]PCBM

PCPDTBT:[70]PCBM films cast from chlorobenzene containing:

- no dithiol
- 1,4-butanedithiol
- 1,6-hexanedithiol
- 1,8-octanedithiol

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

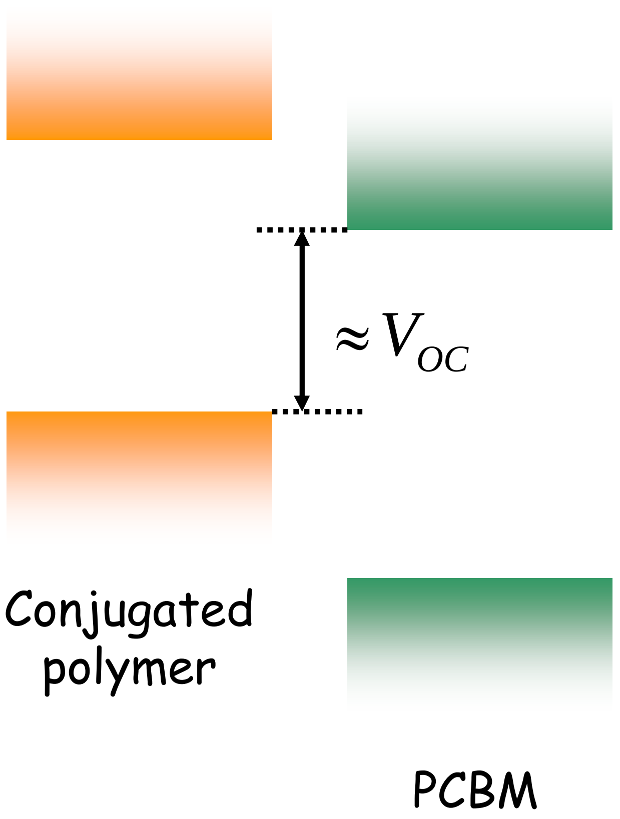
A limiting factor of P3HT: narrow spectral range

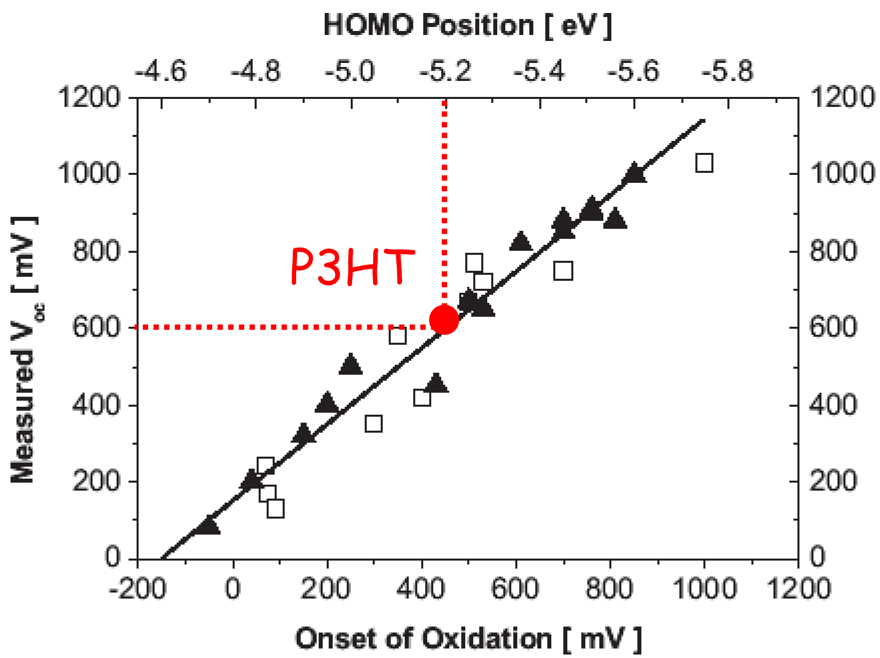


Only 23% of the photons of the AM1.5 spectrum can be absorbed by P3HT!

Deep HOMO-level polymers for higher V_{oc}

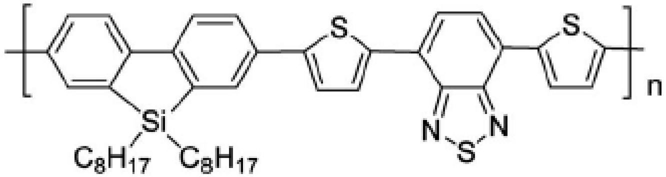
$$V_{OC} \approx \frac{1}{e}\left(HOMO_{Polymer} - LUMO_{PCBM}\right)$$



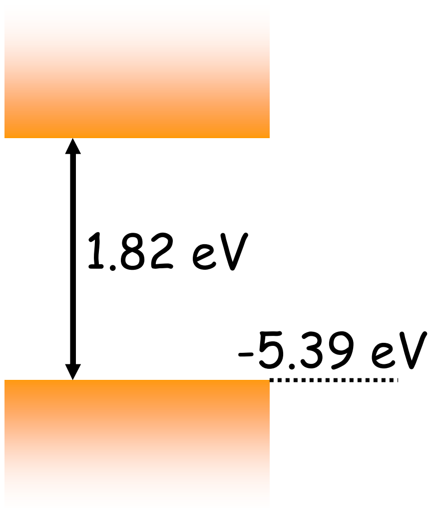


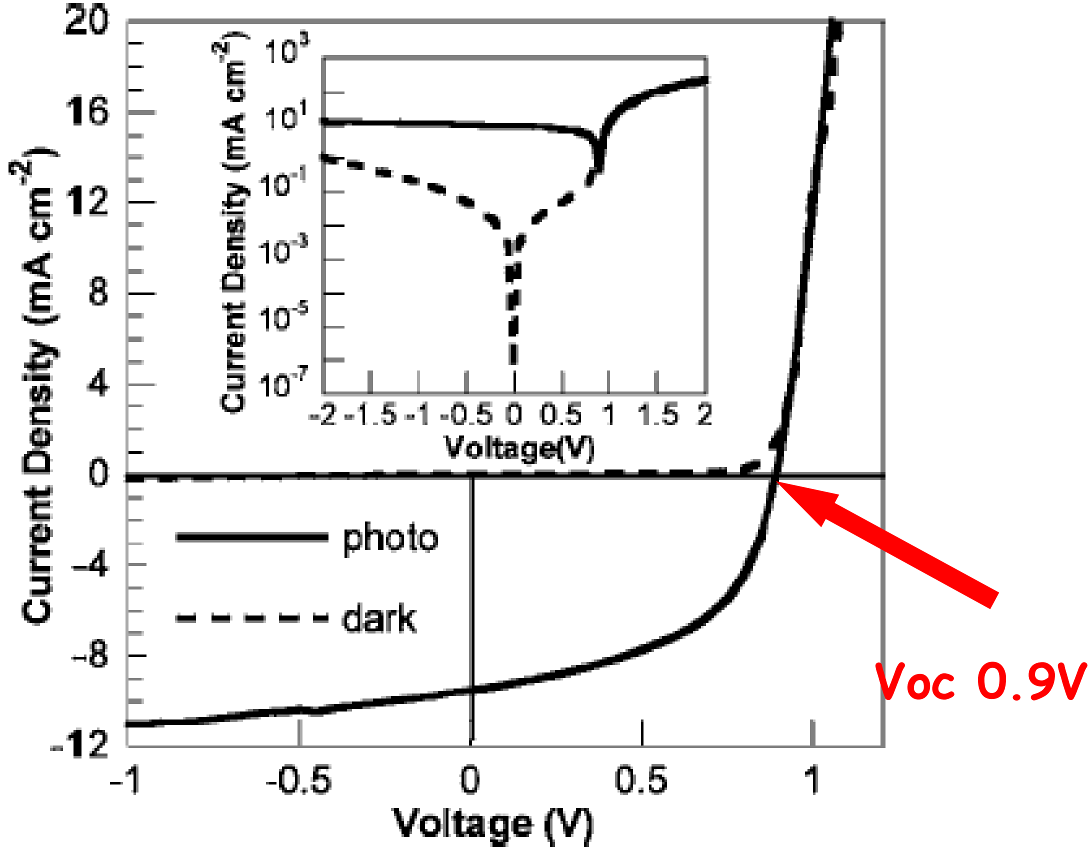
M.C. Scharber et al., *Adv. Mater. 18* (2006) 789

PSiF-DBT:PCBM 1:2 by wt.



PSiF-DBT





E. Wang et al., *Appl. Phys. Lett.* *92* (2008) 033307

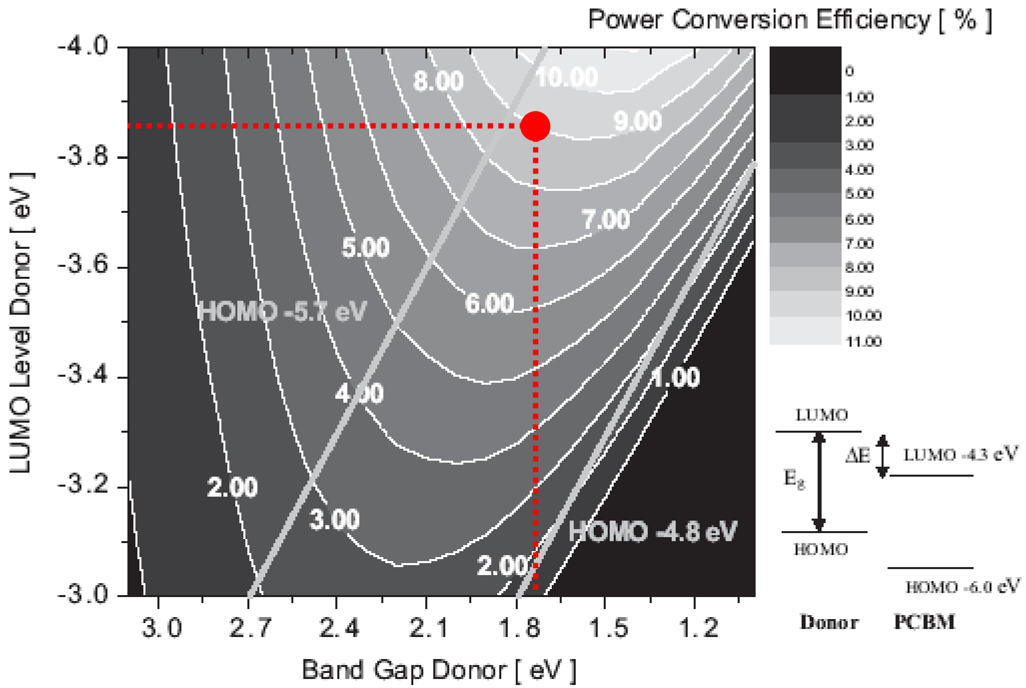
ADVANCED MATERIALS

COMMUNICATIONS

DOI: 10.1002/adma.200501717

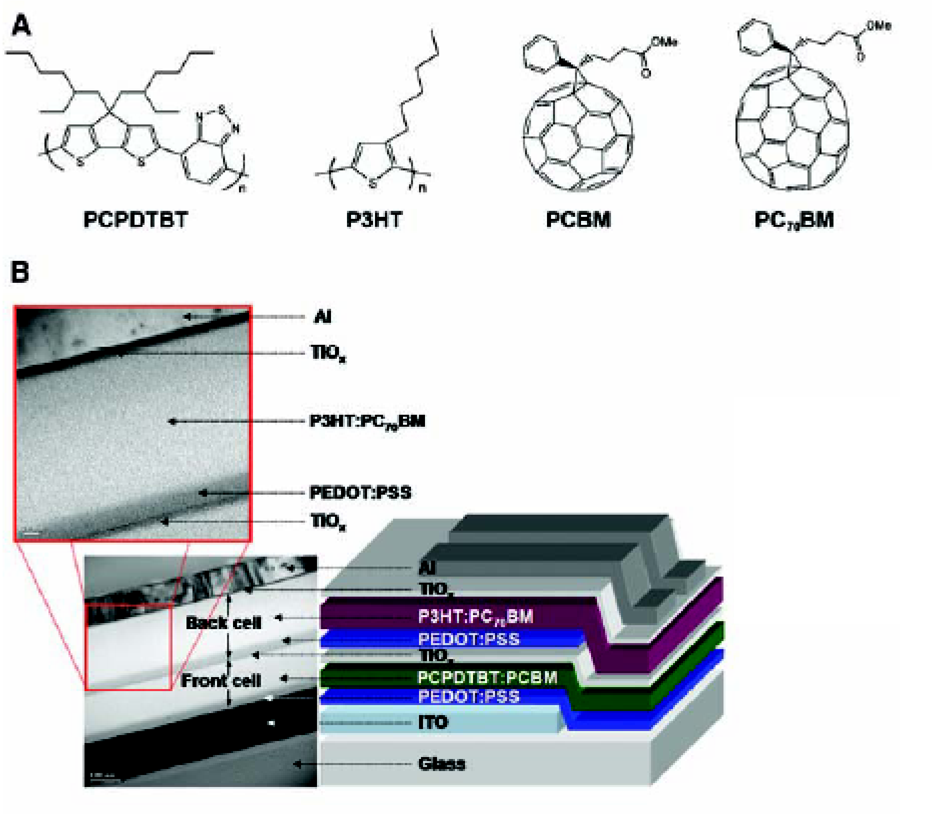
Design Rules for Donors in Bulk-Heterojunction Solar Cells—Towards 10 % Energy-Conversion Efficiency**

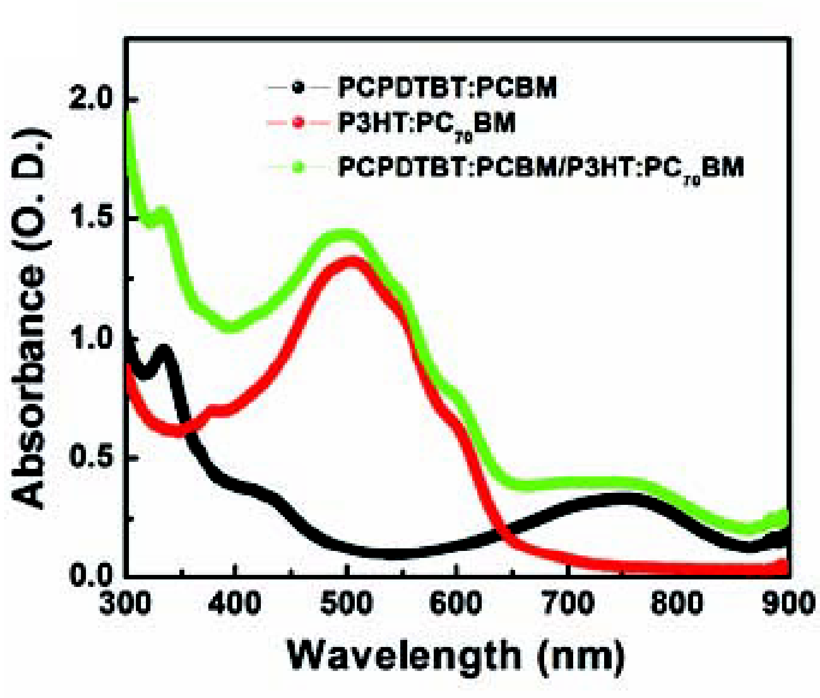
By *Markus C. Scharber,* David Mühlbacher, Markus Koppe, Patrick Denk, Christoph Waldauf, Alan J. Heeger*, and *Christoph J. Brabec*



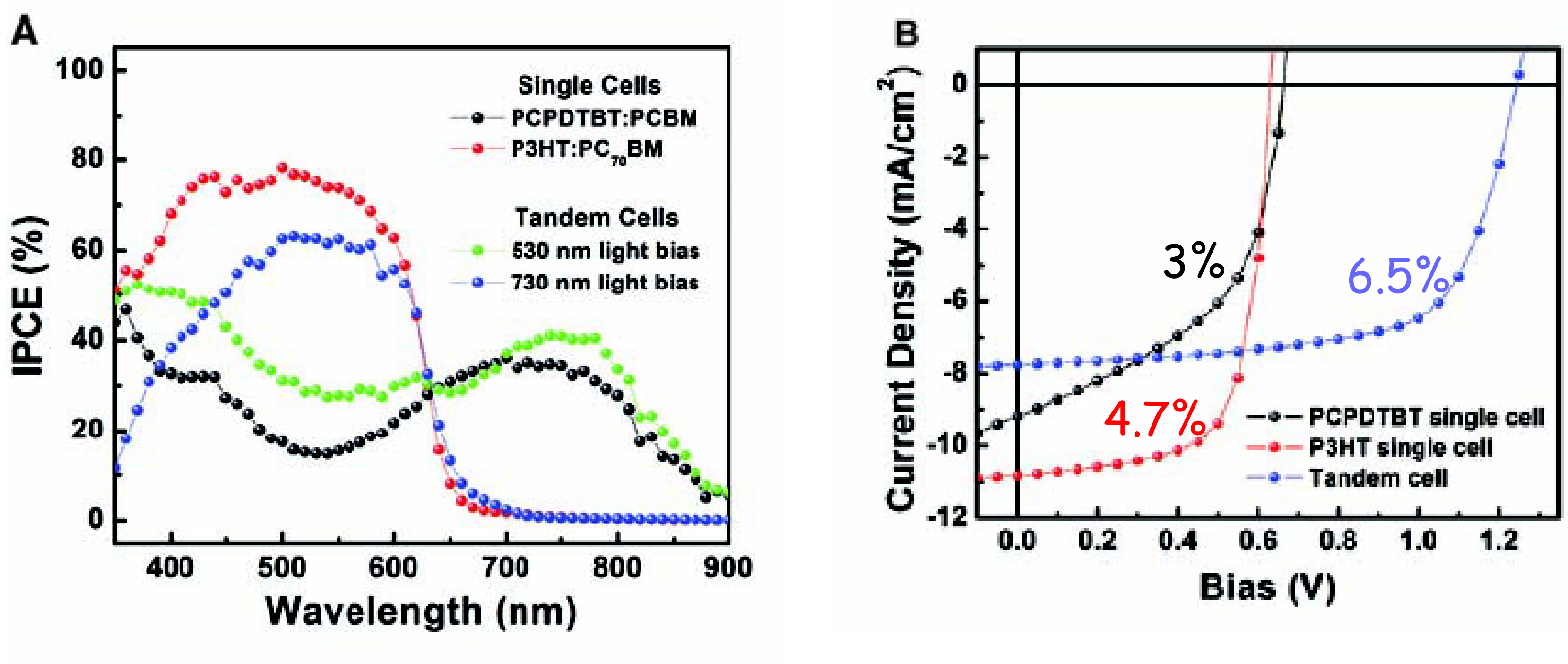
M.C. Scharber et al., *Adv. Mater. 18* (2006) 789

Tandem BHJ solar cells





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



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

ADVANCED MATERIALS

COMMUNICATION

DOI: 10.1002/adma.200702337

Design Rules for Donors in Bulk-Heterojunction Tandem Solar Cells-Towards 15 % Energy-Conversion Efficiency**

By *Gilles Dennler*,* *Markus C. Scharber*, *Tayebeh Ameri*, *Patrick Denk*, *Karen Forberich*, *Christoph Waldauf*, and *Christoph J. Brabec**

Adv. Mater. 20 (2008) 579

Stability of BHJ solar cells

Flexible organic P3HT:PCBM bulk-heterojunction modules
with more than 1 year outdoor lifetime

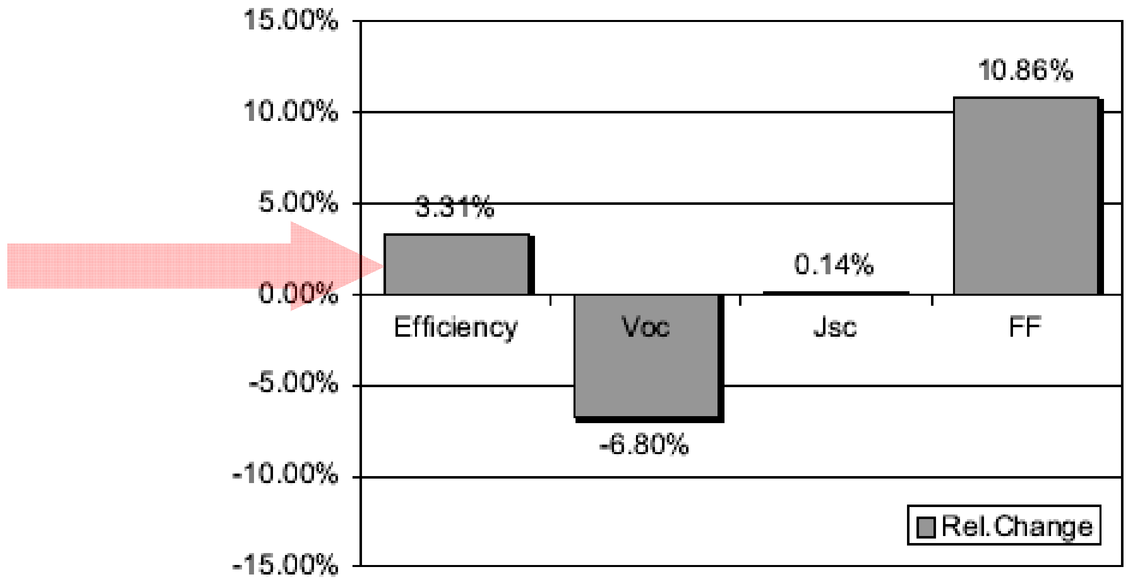


Fig. 4. Relative change of the performance parameters extracted from the *jV*-characteristics of the module, before and after 14 months outdoor degradation.

J. A. Hauch et al., *Solar Energy Materials & Solar Cells 92* (2008) 727

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Konarka Opens World's Largest Roll-to-Roll Thin Film Solar Manufacturing Facility with One Gigawatt Nameplate Capacity

Former Polaroid Facility in New Bedford, Mass. Prepares Konarka for Large Scale Production of Power Plastic® Thin Film Photovoltaics

Lowell, Mass. – Oct. 7, 2008 – Konarka Technologies, Inc., an innovator in development and commercialization of Power Plastic®, a material that converts light to energy, today announced the company has opened the largest roll-to-roll flexible thin film solar manufacturing facility in the world, preparing for the commercialization and mass production of its patent-protected thin film solar material, Power Plastic. Located in New Bedford, Massachusetts, the 250,000 square foot building was previously the location for Polaroid Corporation's most advanced printing technologies.

"This facility has state-of-the-art printing capabilities that are ready for full operation, with the future potential to produce over a gigawatt of flexible plastic solar modules per year," commented Howard Berke, executive chairman and co-founder of Konarka. "Our technical leadership and innovation in flexible thin film solar, along with this facility's capabilities of producing in excess of 10 million square meters of material per year, will allow us to produce Power Plastic for indoor, portable, outdoor and building integrated applications."

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- Enzo Menna
- Giorgia Possamai
- Matteo Valentini
- Carlo Corvaja