DPI DUTCH POLYMER INSTITUTE

# Polymer solar cells
# why, status and challenges

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DPI Annual Meeting, November 25-26, 2008

Technische Universiteit Eindhoven University of Technology

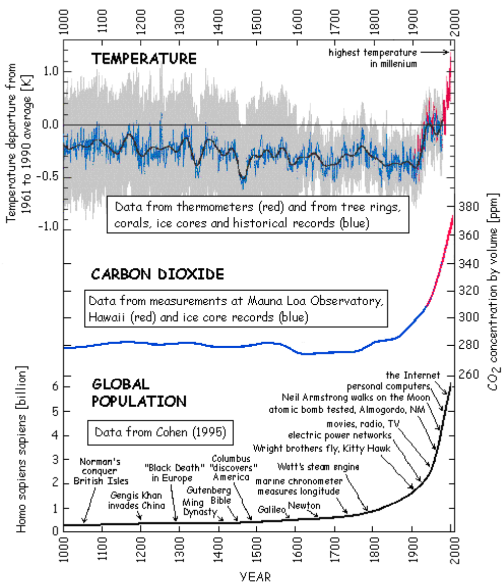
Where innovation starts

## Global warming in the last millennium

**Global energy power demands:**

**2008**
**6.5 Billion people use 12 TW**

**2050**
**8-10 Billion people use 20 TW**




*Source: Marty Hoffert, New York University*

## Only solar energy can provide 20 TW in 2050

**Solar**
100000 TW at Earth surface
10000 TW (technical value)

**Wind**
14 TW

**Tide/Ocean**
Currents
0.7 TW

**Geothermal**
1.9 TW

**Biomass**
5-7 TW

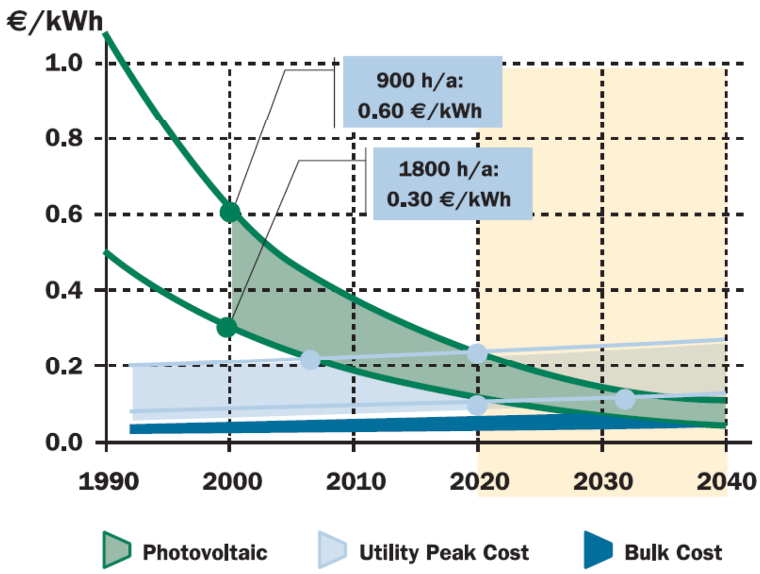
**Hydroelectric**
1.2 TW technically feasible
0.6 TW installed capacity

*Apart from nuclear power, all sources of energy used nowadays (coal, oil, natural gas, biomass, water, wind) ultimately originate from the sun.*

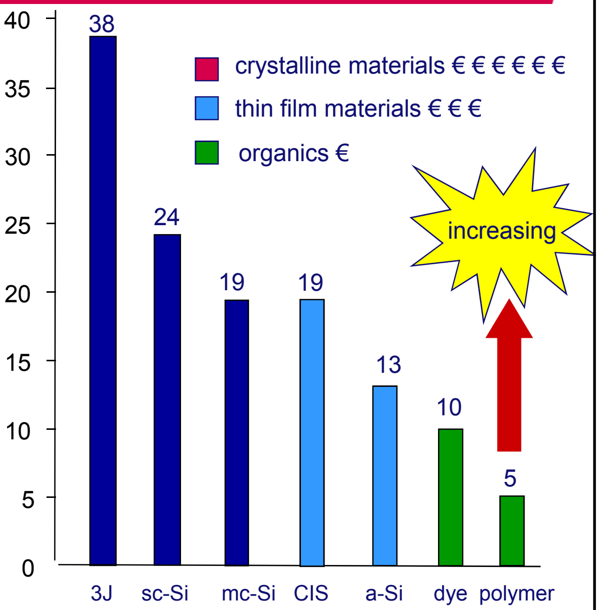
*Source: Arthur Nozik, NREL*

*Courtesy: Christoph Brabec, Konarka*

## What are the costs for producing solar energy?



## Photovoltaic solar cell efficiencies & costs




*Status of 2005*

## How can we reach 20 TW PV-energy in 2050?

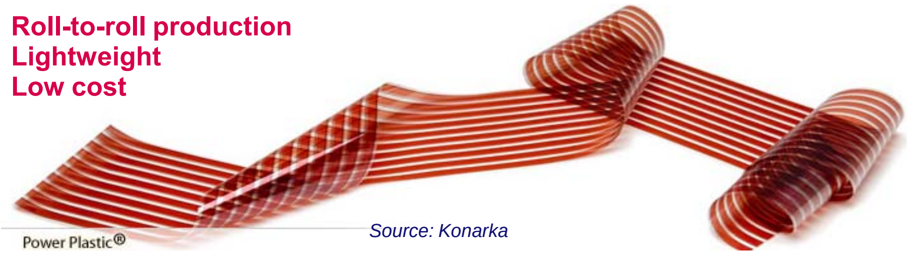
| | |
|---|---|
| Required power: | 20 TW |
| Sunlight: | 1000 W/m$^2$ 12 h a day |
| Efficiency: | 10% |
| Required area: | 400,000 km$^2$ = $20\times10^{12}/(1000 \times 10\% \times 12/24)$ |
| Compare: | 500,000 km$^2$ = Spain |

How can we reach this area in ~30 years?
Required 36.5 km$^2$ solar cells a day

this is a strip of 365 km by 100 m every day for 30 years

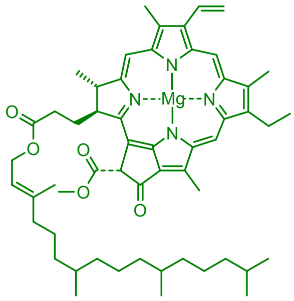
**The (only?) solution : plastic solar cells**

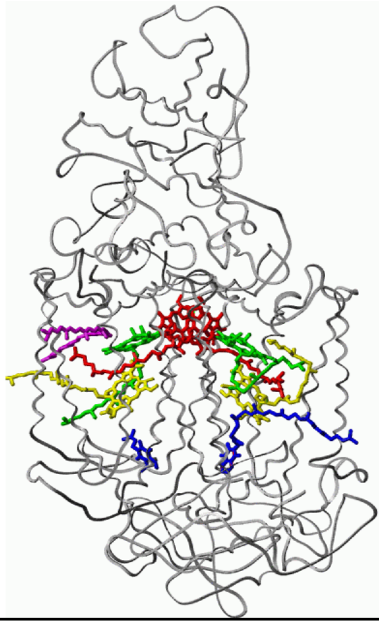
**Roll-to-roll production**
**Lightweight**
**Low cost**



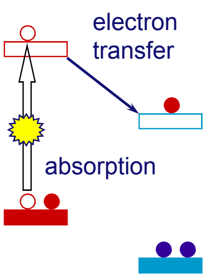

*Source: Konarka*

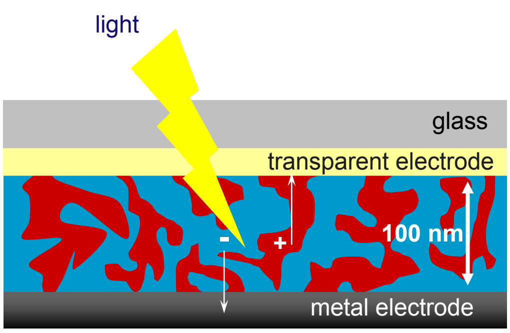
## Photosynthesis : or how coal, oil, gas and biomass are made today



## Bulk-heterojunction solar cells

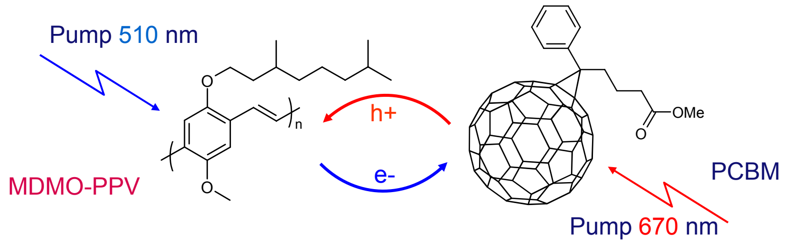


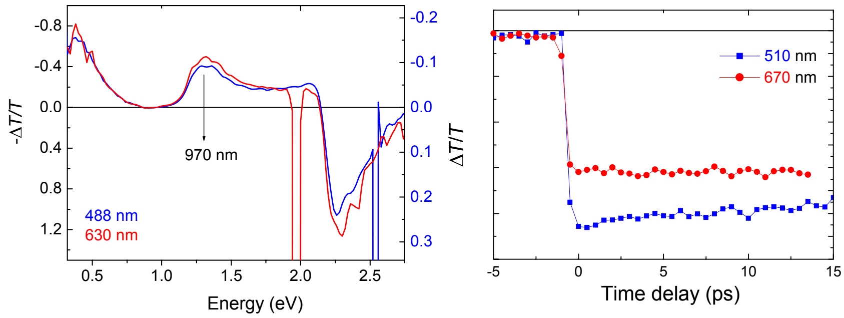




nanoscopic mixing of donor and acceptor to overcome ~10 nm exciton diffusion length

*R. H. Friend et al., Nature 1995, **376**, 498*
*A. J. Heeger et al., Science 1995, **270**, 1789*

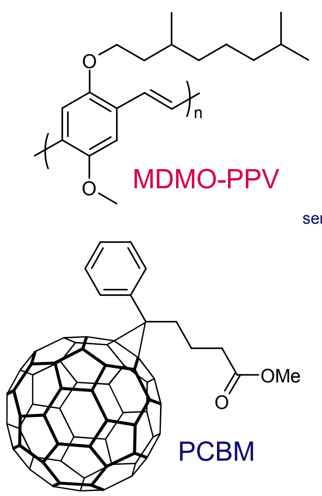
## Sub-picosecond hole and electron transfer

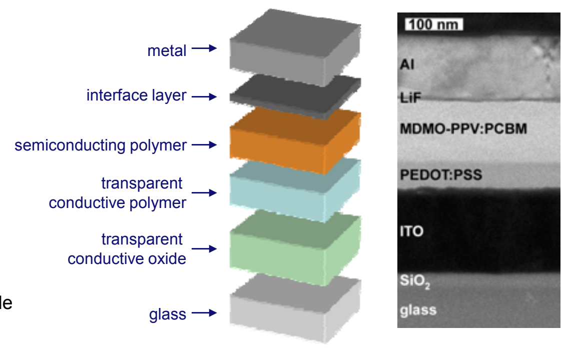



*Paul van Hal, Appl. Phys. A. 2004 , **79**, 41.*

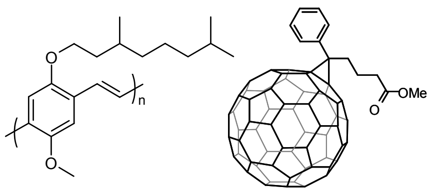
## Polymer solar cells contain two components: electron donor and electron acceptor



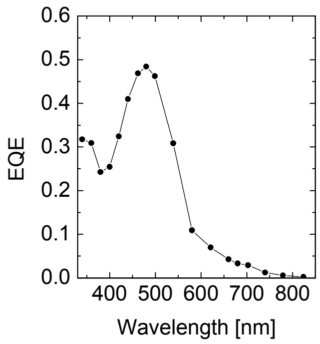



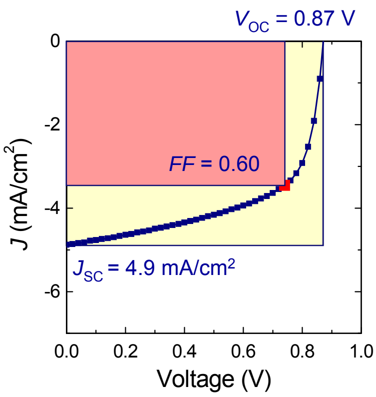

*Sean Shaheen et al., Appl. Phys. Lett. 2001, **78**, 841*
*Jeroen van Duren, Adv. Funct. Mater. 2002, **12**, 665.*

## 2.5% efficient organic plastic solar cells



MDMO-PPV    PCBM

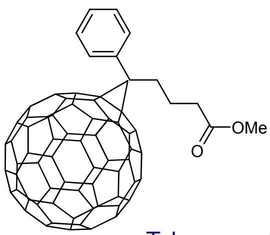


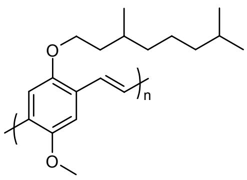




$$FF = \frac{(V \times I)_{max}}{V_{oc} \times I_{sc}} \leq 1$$

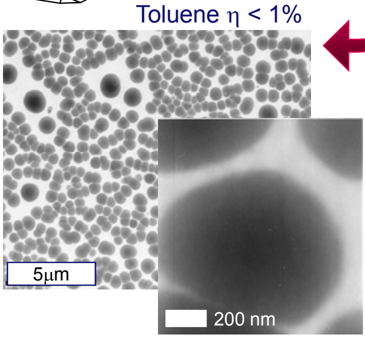
*Sean Shaheen et al., Appl. Phys. Lett. 2001, **78**, 841*
*Martijn Wienk (ECN) and Jeroen van Duren (TU/e)*

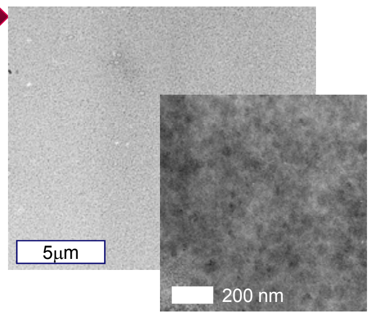
## Importance of processing and morphology



Toluene η < 1%    Chlorobenzene η > 2.5 %

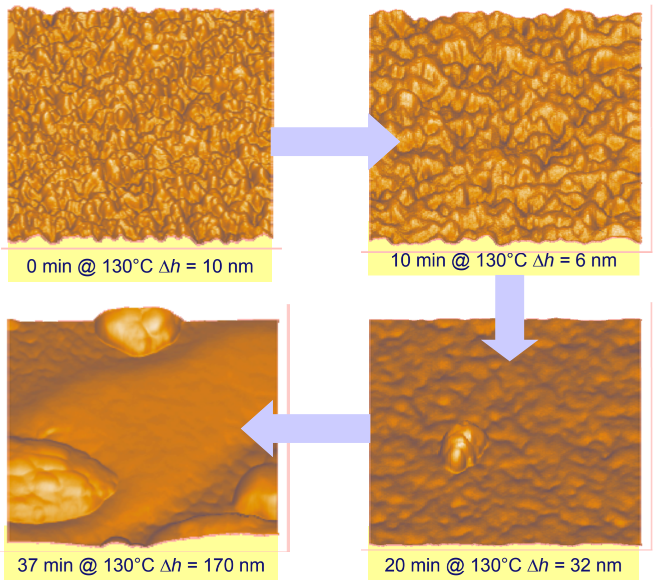


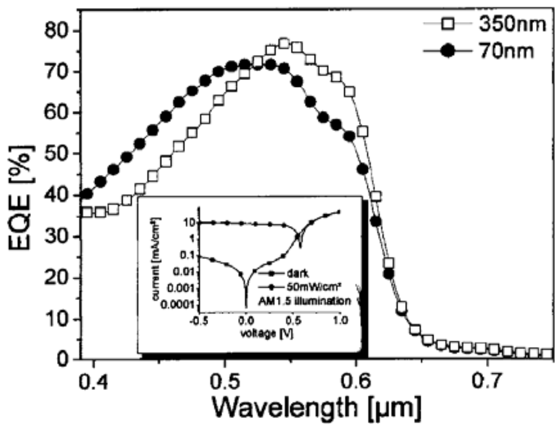

*see also: T. Martens et al., Synth. Met. 2003, **138**, 243*

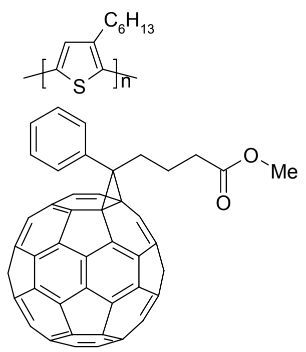
*Joachim Loos and Xiaoniu Yang (TU/e)*

## Phase separation at higher temperatures




## More efficient P3HT:PCBM solar cells




$I_{sc}$ = 8.7 mA/cm$^2$

$V_{oc}$ = 580 mV

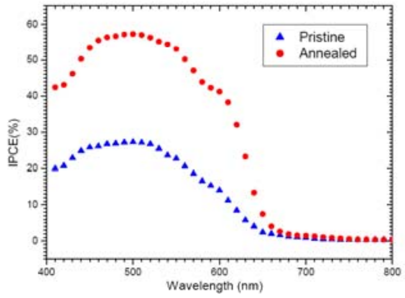
FF = 0.55

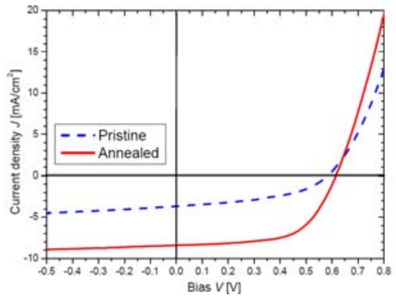
$\eta_e$ = 2.8%.

*Pavel Schilinsky, Appl. Phys. Lett. 2002, **81**, 3885*
*Franz Padinger, Adv. Funct. Mater 2003, **13**, 85*

# Annealing of P3HT:PCBM solar cells

annealing at 120 °C for 60 min on complete devices




regioregular P3HT
$M_w$ = 100000 g mol$^{-1}$
$M_w/M_n$ = 2.14

$V_{oc}$ = 0.615 V
$FF$ = 0.61
$J_{sc}$ = 7.2 mA cm$^{-2}$
$\eta_e$ = 2.7 %
AM1.5 1000 W/m$^2$

*Xiaoniu Yang, TU/e*

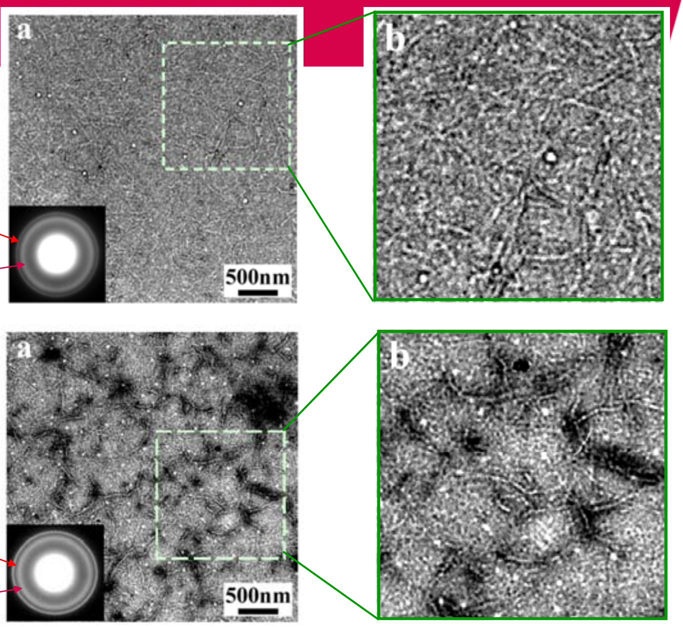
# TEM

after spin coating
from chlorobenzene

P3HT
0.39 nm*
PCBM
0.46 nm

after annealing
at 110 °C for
60 min

P3HT
0.39 nm*
PCBM
0.46 nm




* P3HT whiskers: K.J. Ihn, J. Moulton, P. Smith, *J. Polym. Sci. Part B: Polym. Phys.* **1993**, ***31,*** 735.

## What makes an solar cell efficient?

**Absorption efficiency**

**Or how many photons are absorbed?**

**Quantum efficiency**

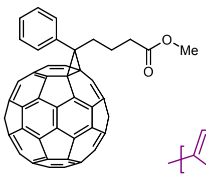
**Or how many photons are converted into electrons?**

**Energy efficiency**

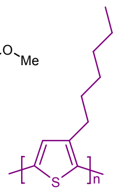
**Or what is the final (chemical) potential of the electrons generated?**

**Shockley-Queisser limit: 31% efficiency for a single junction cell**

## Losses in P3HT:PCBM cells




PCBM

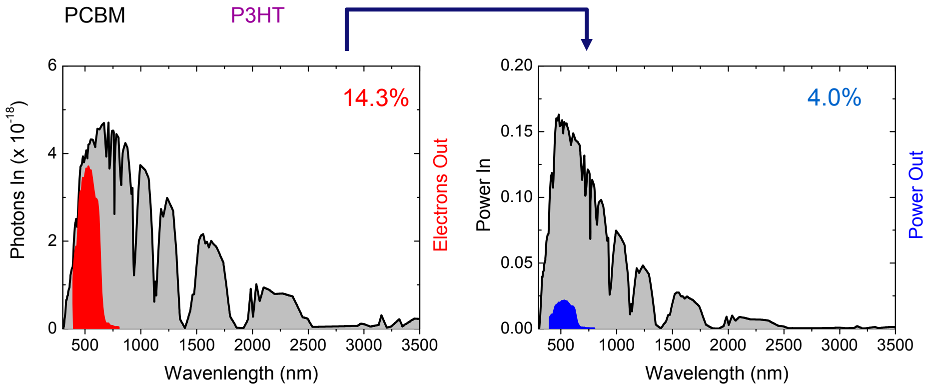



P3HT

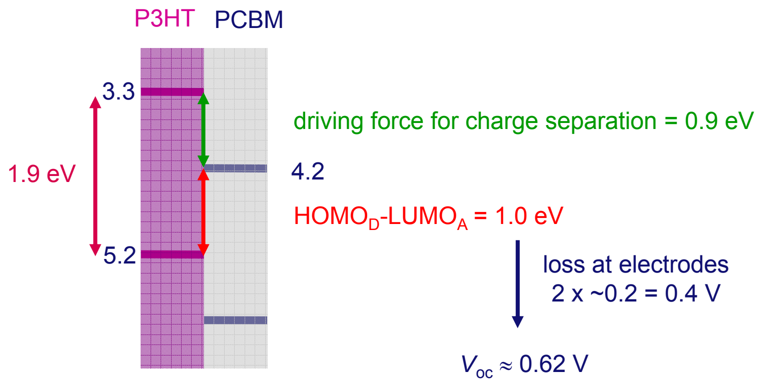
photon energy > 1.9 eV !!!!!

FF = 0.65

$V_{oc}$ = 0.62 V

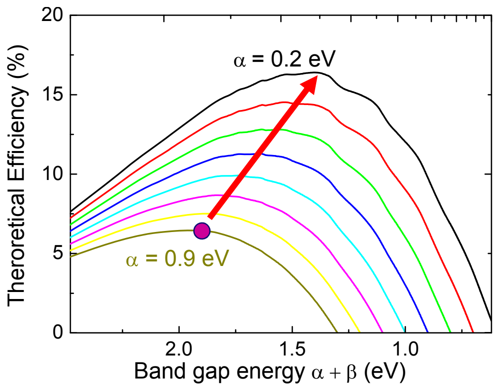


## Voltage loss: 1.9 → 0.6 eV



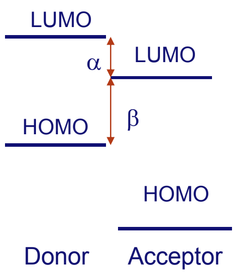

*J. Halls et al., Phys Rev B. 1999,* ***60****, 5721*
*V. Mihailetchi et al., J. Appl. Phys. 2003,* ***94****, 6849*
*M. C. Scharber et al., Adv. Mater. 2006,* ***18****, 789*

## Theoretical efficiencies




assuming: FF = 0.7, EQE = 0.9 and 0.2 V loss at each electrode

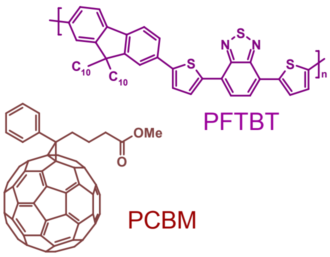
$E_g$ = α+β
$V_{oc}$ ≈ β - 0.4 V




Goal: α+β ≈ 1.4 eV
α small

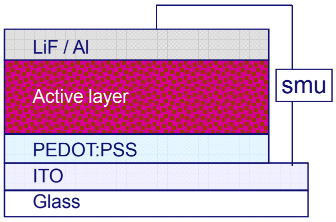
*Martijn Wienk (TU/e)*

## PFTBT:PCBM (80 wt. %) solar cells: 4.2%

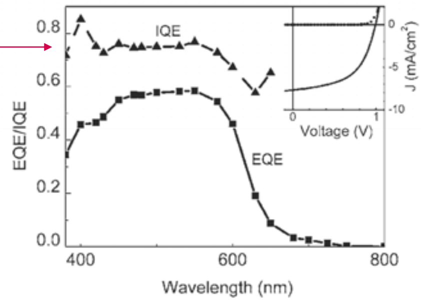


PFTBT

PCBM



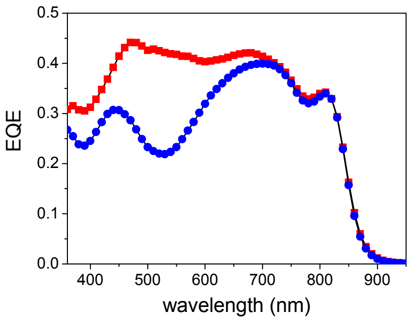

75 % of the absorbed photons generate current

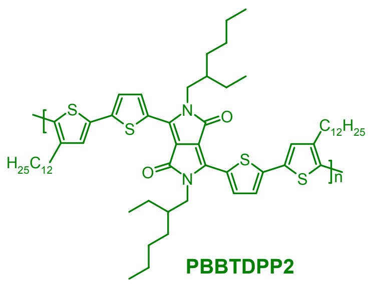



$V_{oc}$ = 1.0 V
$FF$ = 0.54
$J_{sc}$ = 7.7 mA/cm$^2$
$\eta_e$ = 4.2 %
AM1.5 1000 W/m$^2$

*Lenneke Slooff, Appl. Phys. Lett. 2007, **90**, 143506*
*O. Inganäs & M. R. Andersson, Adv. Mater. 2003, **15**, 988*

## PBBTDPP2:PCBM solar cells: 4%



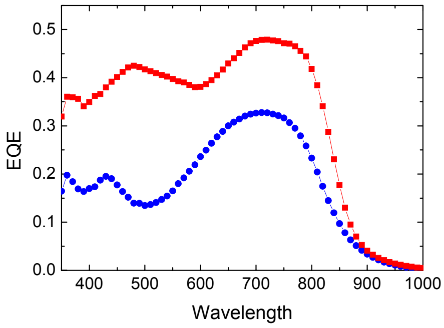



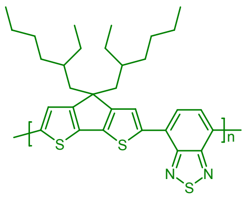
PBBTDPP2

| Ratio 1:2 | $J_{sc}$ (mA/cm$^2$) | $FF$ | $V_{oc}$ (V) | $\eta$ (%) |
|---|---|---|---|---|
| PBBTDPP2:[60]PCBM | 9.4 | 0.54 | 0.63 | 3.2 |
| PBBTDPP2:[70]PCBM | 11.3 | 0.58 | 0.61 | 4.0 |

*M. Wienk, J. Gilot, M. Turbiez, Adv. Mater. 2008, **20**, 2556*

## PCDTPBT:PCBM solar cells: ~4%



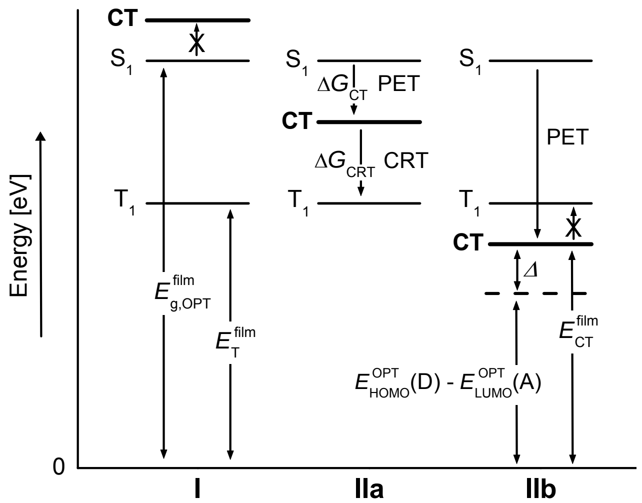

$E_g$ = 1.40 eV

| Ratio 1:2 | $J_{sc}$ (mA/cm²) | *FF* | $V_{oc}$ (V) | $\eta$ (%) |
|---|---|---|---|---|
| PCPDTBT:[60]PCBM | 7.2 | 0.42 | 0.69 | 2.4 |
| PCPDTBT:[70]PCBM | 12.7 | 0.49 | 0.61 | 3.8 |

*Munazza Shahid, Jan Gilot (TU/e)*

*Muhlbacher, Adv. Mater. 2006, **18**, 2884.* *Peet, Nature. Mater. 2007, **6**, 497.*

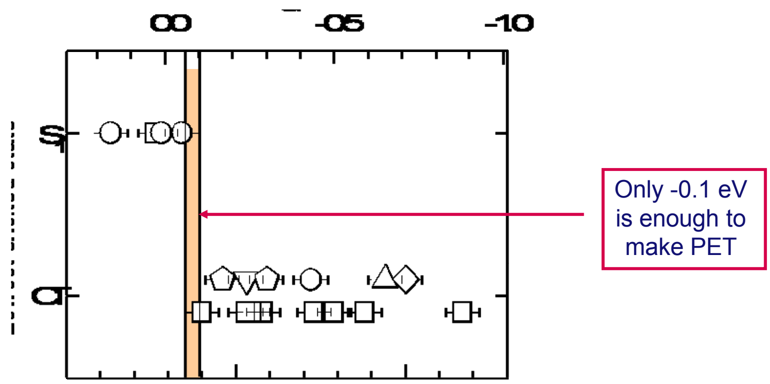
## Where is the limit?




$S_1$ and $T_1$ represent the lowest singlet and triplet states in the D – A combination

## Results from 18 D-A blends in PET

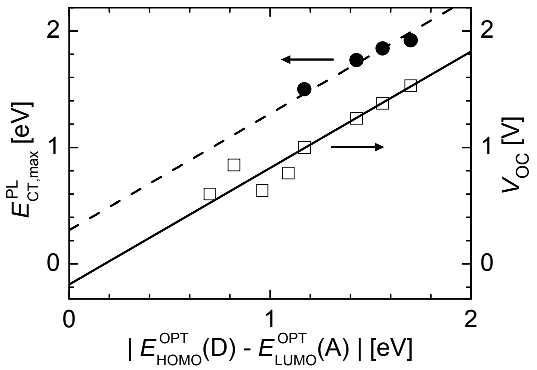
$$\Delta G_{CT} = E_{CT} - E_g = |E^{OPT}_{HOMO}(D) - E^{OPT}_{LUMO}(A)| + 0.29 - E_g$$




from optical photoinduced absorption, fluorescence, and cell performance

## Effective levels scale with $E_{CT}$ and $V_{oc}$

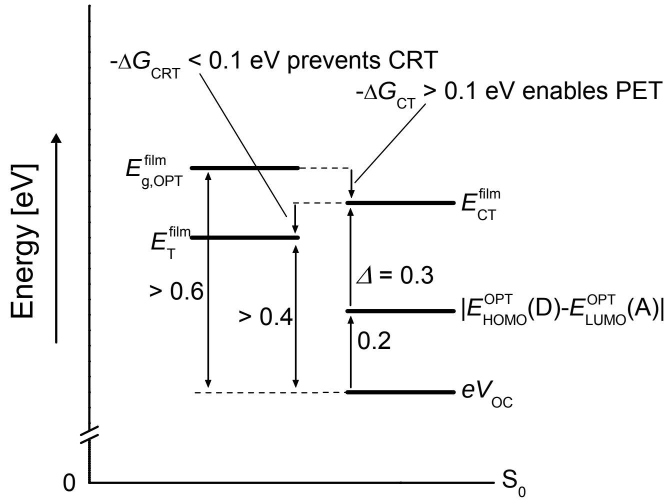
Implication: There is a loss of 0.5 eV going from $E_{CT}$ to $V_{oc}$




$$E_{CT} = |E^{OPT}_{HOMO}(D) - E^{OPT}_{LUMO}(A)| + 0.29 \quad \text{eV}$$

$$eV_{oc} = |E^{OPT}_{HOMO}(D) - E^{OPT}_{LUMO}(A)| - 0.18 \quad \text{eV}$$

# Minimal energy losses?




Conclusion: There will be at least 0.6 eV loss from $E_g$ to $V_{OC}$

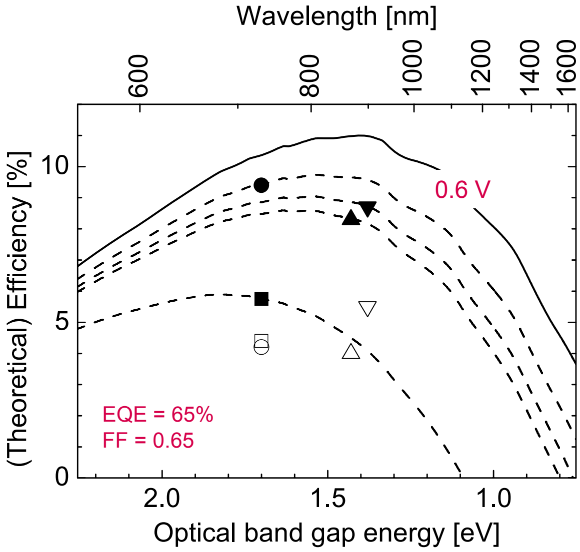
*Dirk Veldman (TU/e)*

# How is this in good cells?

| ***Polymer bulk-heterojunctions*** | $E_g$ | $V_{oc}$ | $E_g$-$V_{oc}$ | $\eta$ |
|---|---|---|---|---|
| PCPDTBT : [70]PCBM | 1.38 | 0.62 | 0.76 | 5.5 |
| PSiF-DBT : [60]PCBM | 1.70 | 0.90 | 0.80 | 5.4 |
| P3HT : [60]PCBM | 1.70 | 0.61 | 1.09 | 4.4 |
| PF10TBT : [60]PCBM | 1.70 | 1.00 | 0.70 | 4.2 |
| PBBTDPP2 : [70]PCBM | 1.43 | 0.61 | 0.82 | 4.0 |
| MDMO-PPV : [70]PCBM | 1.70 | 0.77 | 0.93 | 3.0 |
| *Small molecule heterojunctions* | | | | |
| CuPc : $C_{60}$ | 1.55 | 0.54 | 1.01 | 5.0 |
| DCV5T / $C_{60}$ | 1.77 | 0.79 | 0.79 | 3.4 |

*Dirk Veldman (TU/e)*

## Refinement




PF10TBT:[60]PCBM (0.70 eV, ●, ○),

PCPDTBT:[70]PCBM (0.76 eV, ▼, ▽),

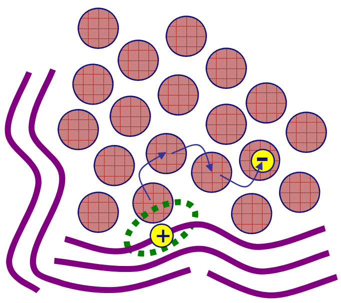
PBBTDPP2:[70]PCBM (0.80 eV, ▲, △)

P3HT:[60]PCBM (1.09 eV, ■, □).

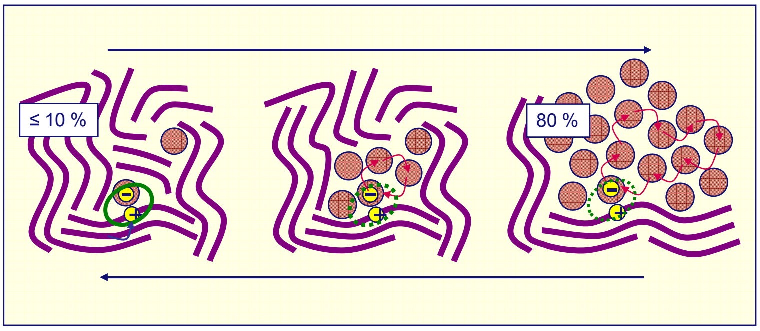
So we may hope for ~11%

## Charge generation in polymer solar cells

Efficiencies of polymer solar cells are increasing to ~5% recently.
Do we really understand the fundamental processes?



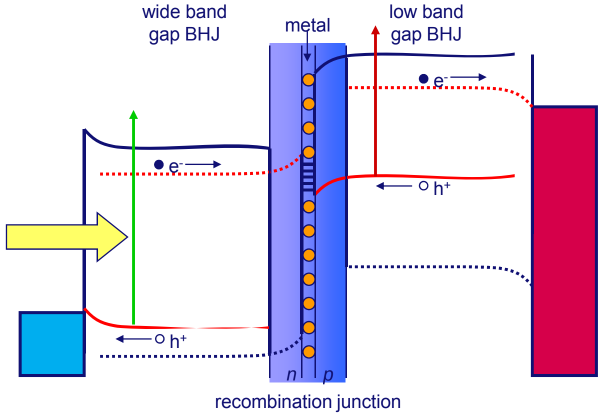
## Charge separation only partly understood?




Scientific question:

What are the requirements for full charge separation art very low electrical fields?

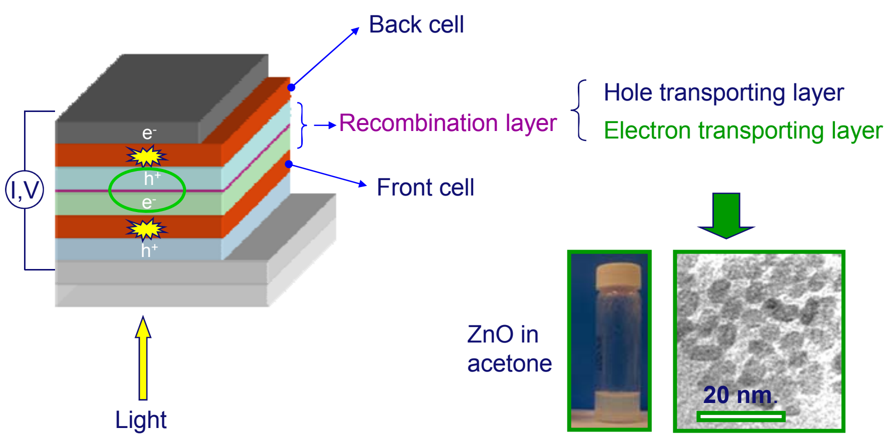
## Multi-junction polymer solar cells



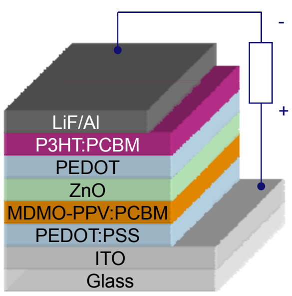

AM1.5 1000 W/m²

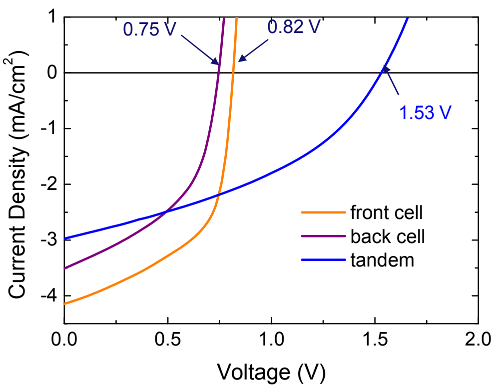
30% for a single band gap cell
42% for a tandem cell
49% for a triple junction device
68% for an infinite stack

## Aim: create transparent electron and hole transporting layers to recombine charges




## Solution-processed double junction solar cell

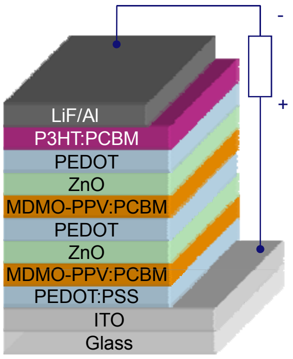


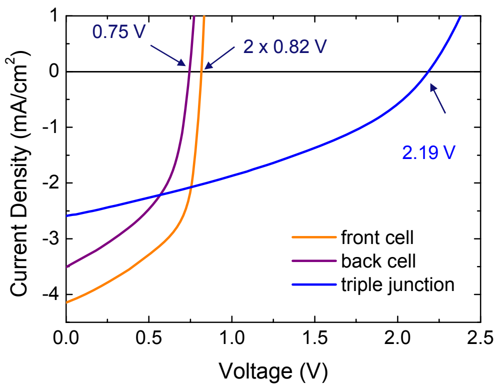




$V_{oc}$ = 1.53 V
$I_{sc}$ = 3.0 mA/cm$^2$
FF = 0.40
MPP = 1.8 mW/cm$^2$

*Jan Gilot, Appl. Phys. Lett. 2007, **90**, 143512*

## Solution-processed triple junction solar cell



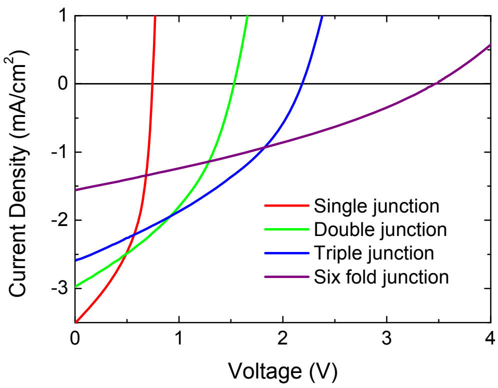

8 solution processed layers on top of each other
processing time ~10 min.

$V_{oc}$ = 2.19 V
$I_{sc}$ = 2.6 mA/cm$^2$
FF = 0.37
MPP = 2.1 mW/cm$^2$

*Jan Gilot, Appl. Phys. Lett. 2007, **90**, 143512*

## Large stacks: six-fold junction

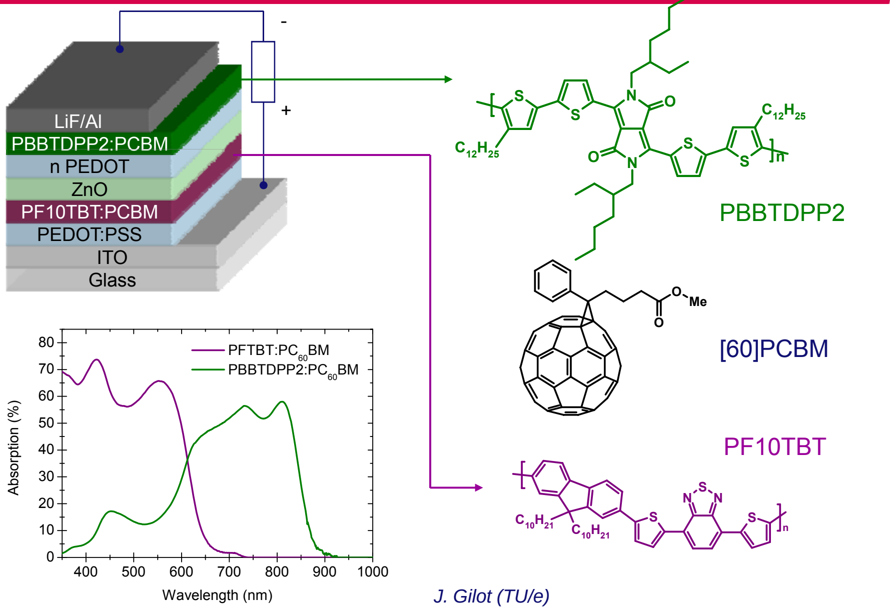
17 solution processed layers on top of each other





| Single Junction | Double Junction | Triple Junction | Six-fold Junction |
|---|---|---|---|
| $V_{oc}$ = 0.75 V | $V_{oc}$ = 1.53 V | $V_{oc}$ = 2.19 V | $V_{oc}$ = 3.46 V |
| $I_{sc}$ = 3.5 mA/cm$^2$ | $I_{sc}$ = 3.0 mA/cm$^2$ | $I_{sc}$ = 2.6 mA/cm$^2$ | $I_{sc}$ = 1.6 mA/cm$^2$ |
| FF = 0.48 | FF = 0.40 | FF = 0.37 | FF = 0.32 |
| MPP = 1.3 mW/cm$^2$ | MPP = 1.8 mW/cm$^2$ | MPP = 2.1 mW/cm$^2$ | MPP = 1.7 mW/cm$^2$ |

## Tandem solar cell using different band gaps

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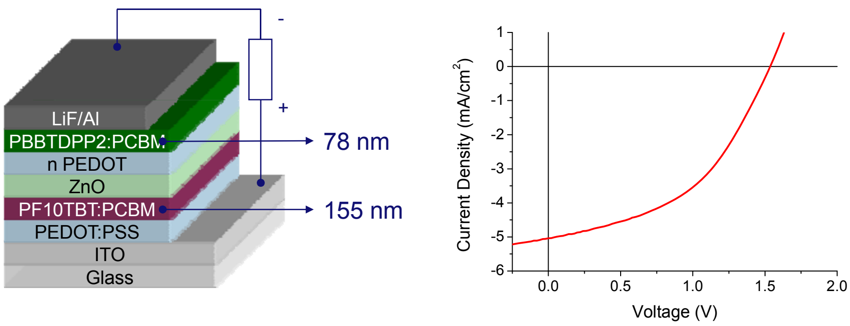
## Preliminary performance




| TU/e | Solar simulator (ECN) |
|---|---|
| $J_{SC}$ (SR) = 5.3 mA/cm² | **$J_{SC}$ (SS) = 5.0 mA/cm²** |
| $V_{OC}$ = 1.57 V | **$V_{OC}$ = 1.54 V** |
| $FF$ = 0.47 | **$FF$ = 0.46** |
| $\eta_{est}$ = 3.9 % | **$\eta$ = 3.6 %** |

one month later

*J. Gilot (TU/e)*

after UV illumination

## To remember and think about

Renewable energy is a must for our future society

Polymer solar cells might be an option to contribute to that goal
because of speed of production at low cost

Efficiencies of about 10% seem within reach but are a challenging goal

New cell designs and concepts may increase efficiencies to ~15%


## Acknowledgement

*TU/e*
Dirk Veldman
Jan Gilot
Stefan Meskers
Martijn Wienk
Arjan Zoombelt
Munazza Shahid
Shahid Ashraf
Johan Bijleveld

Joachim Loos
Svetlana van Bavel

*ECN*
Sjoerd Veenstra
Jan Kroon

*RUG*
Paul Blom
Bert de Boer

*TNO*
Marc Koetse
Jorgen Sweelssen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