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Recent progress in organic solar cells: From a lab curiosity to a serious photovoltaic technology

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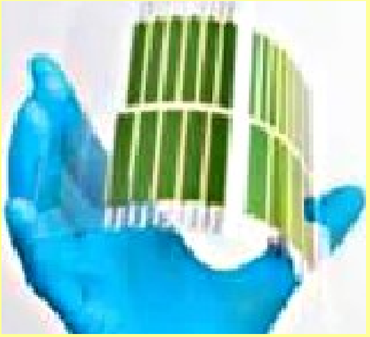
Motivation? Not needed...

Organic Semiconductors

- Large area & flexible substrates possible
- Large variety of carbon-based materials
- Low cost: approx. 1g/m^2 active material

Organic materials

Organic light emitting diodes



Photovoltaic cells

Transistors and memory

Progression of Organic Products

1st wave: OLED Displays

2nd wave: OLED lighting

3rd wave: Solar cells

4th wave: Organic electronics

Time

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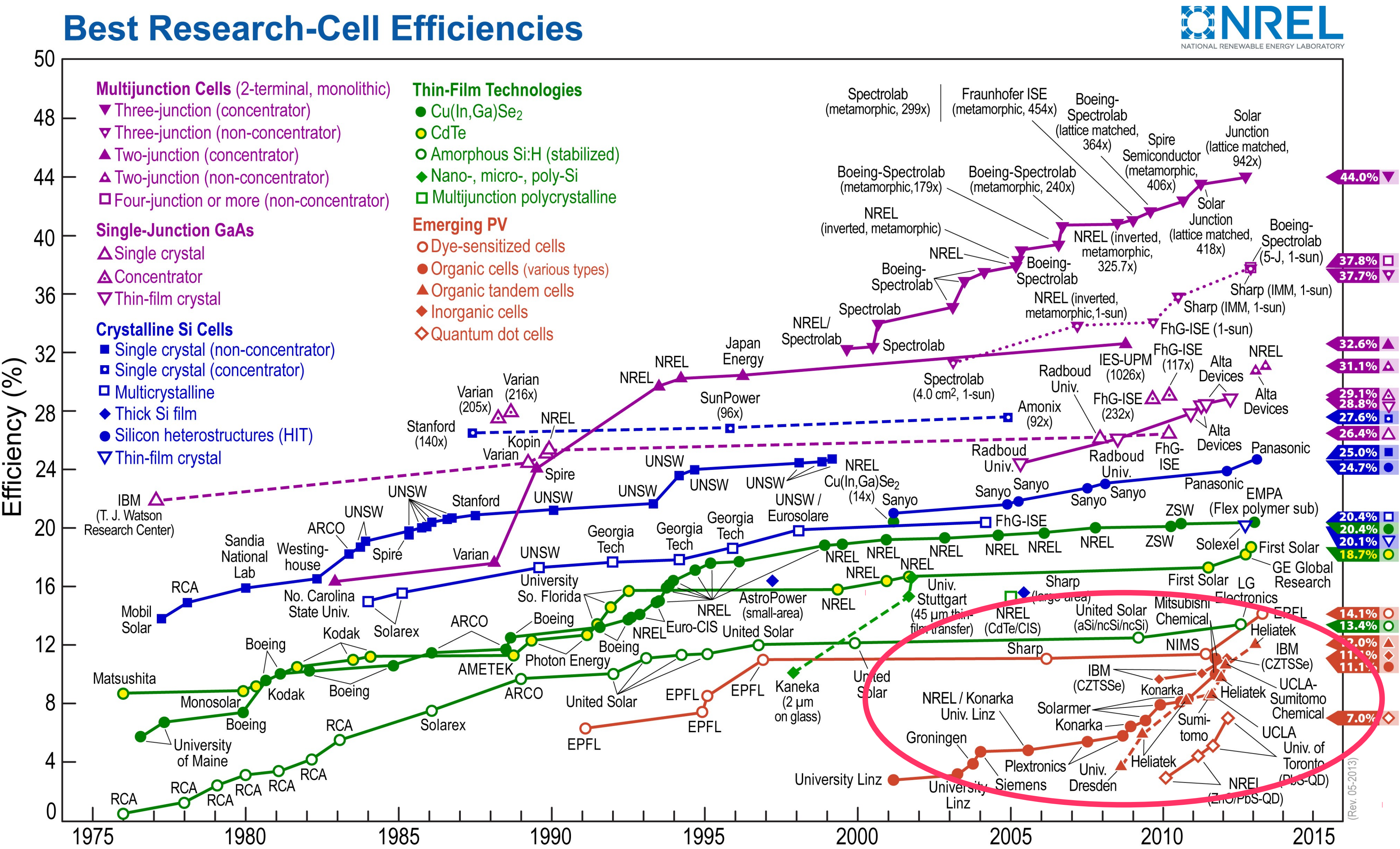
Potential of Organic Photovoltaics

iapp

- Flexible plastic substrates and thin organic layers
  - Low material and energy consumption
  - Short energy payback time
- Potentially transparent, color adjustable
- Compatible with low-cost large-area production technologies

Images: Konarka, Neuber, Heliatek, IAPP

NREL record chart



What will make organic PV a success?

- Often heard opinions about organic PV:
  - „Whatever efficiency, if OPV is cheap enough, it will be competitive....
  - „Five years lifetime is OK, we can exchange the modules“
- We need high efficiency (>15%), long lifetime (>20yrs) and low cost (<<50C/Wp)
- Main arguments for higher efficiency:
  - Electricity generation cost
  - Energy payback time
  - Limited areas available

Cost estimate for OPV

Kalowekamo&Baker, Solar Energy **83**, 1224 (2009)

Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Solar Energy 83 (2009) 1224–1231
SOLAR ENERGY
www.elsevier.com/locate/solener

Estimating the manufacturing cost of purely organic solar cells

Joseph Kalowekamo [1], Erin Baker *

In this paper we estimate the manufacturing cost of purely organic solar cells. We find a very large range since the technology is still very young. We estimate that the manufacturing cost for purely organic solar cells will range between \$50 and \$140/m^2. Under the assumption of 5% efficiency, this leads to a module cost of between \$1.00 and \$2.83/W_p. Under the assumption of a 5-year lifetime, this leads to a levelized cost of electricity (LEC) of between 49¢ and 85¢/kWh. In order to achieve a more competitive COE of about 7¢/kWh, we would need to increase efficiency to 15% and lifetime to between 15–20 years.

… In order to achieve a more competitive cost of electricity...we would need to increase efficiency to 15% and lifetime to between 15–20 years....

Cost components

- Cost calculations have large degree of uncertainty
- Materials cost alone are significant

Cost Component	OSC		
	Type used	Cost estimate ($/m^2)	
		Low	High
Semiconductor	C_{60}, CuPc & SnPc	3.30	5.00
Electrical contacts and interconnects	Aluminum, silver paint	3.40	5.00
Substrate[a]	Flexible Plastic, ITO	7.90	13.68
Protective cover	Flexible encapsulant	2.90	4.40
Sealant	Surlyn	2.90	4.40
Packaging material	–	2.00	3.00
Specialty chemicals	4 TBP	1.00	2.00
Other (absorbing dye; catalyst; electrolyte	N/A	N/A	N/A
Total		23.40	37.48

Kalowekamo&Baker, Solar Energy **83**, 1224 (2009)

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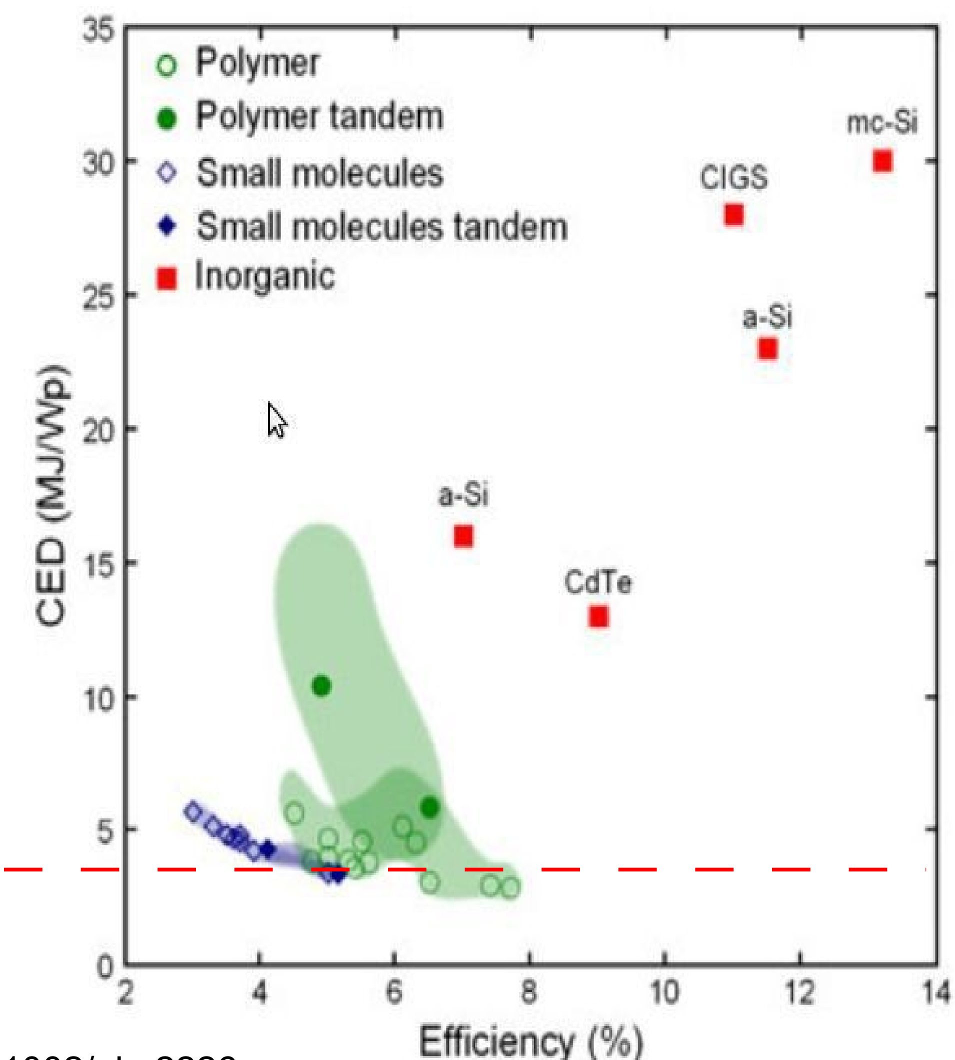
Total		23.40	37.48

about $2/gram

Kalowekamo&Baker, Solar Energy **83**, 1224 (2009)

Energy payback comparison

- Energy payback time:
- Organics clearly ahead
- Payback times <1 year possible with organics
- Go for high-efficiency !



Typical yearly yield Germany

A. Anctil et al., Progr. in Photovoltaics 2012, DOI: 10.1002/pip.2226

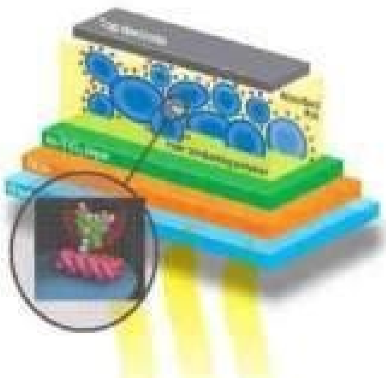
Outline

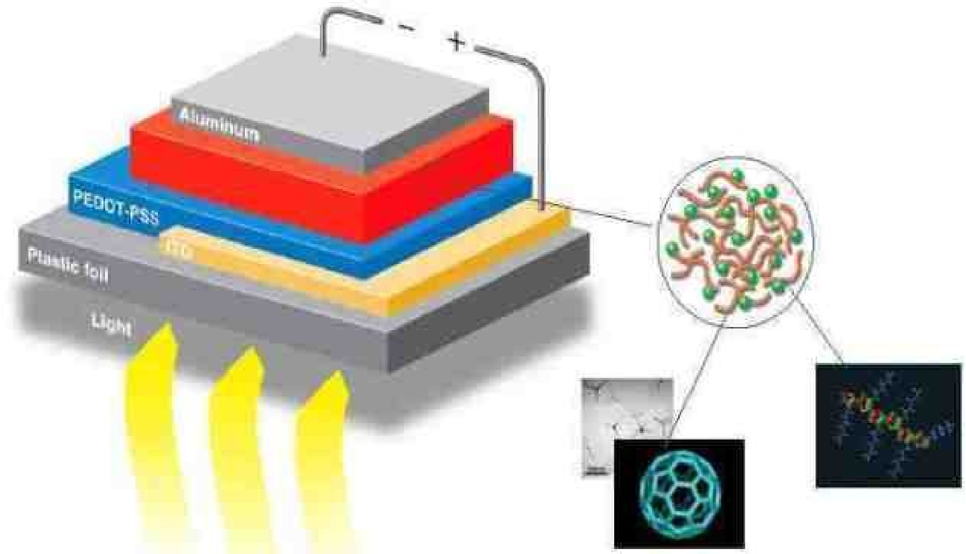
- Motivation
- **Basics of organic solar cells**
- Materials requirements for organic solar cells
- Exploring the thiophene zoo
- Tandem organic cells
- Lifetime&Manufacturing

Classes of Organic PV

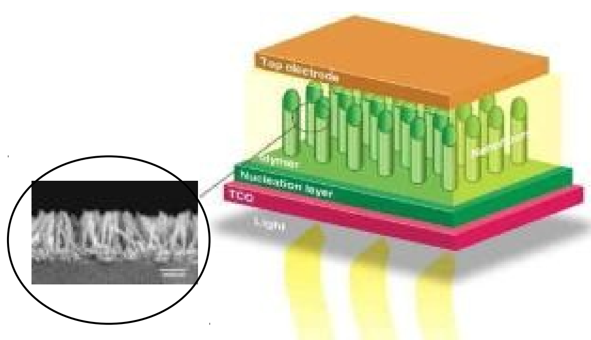
Polymer/small-molecule heterojunction

Dye-sensitized solar cell





Hybrid organic-inorganic

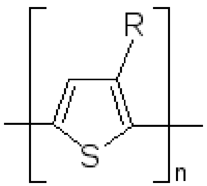


Anders Hagfeldt
Today 14:20

Classification of Organic Solar Cells

Solution Processing

Polymers&small molecules

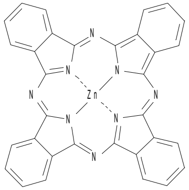


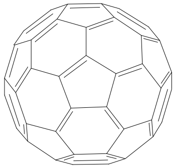
- Layers made by e.g. printing
- High production speeds possible
- Room temperature process

Rene Janssen, today 13:20

Vacuum Sublimation

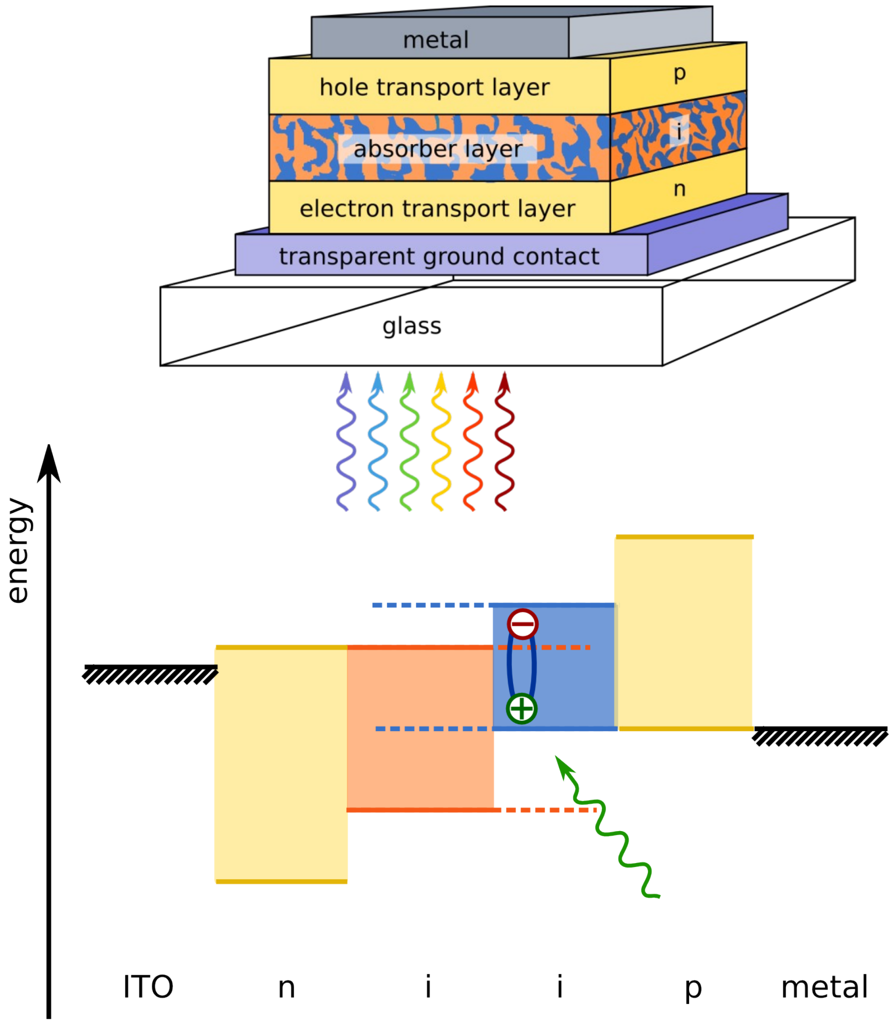
Only small molecules





- Layers made by sublimation of material in vacuum
- Easy access to multi-layer systems
- High material purity

Elementary processes in organic solar cells



absorption

exciton diffusion

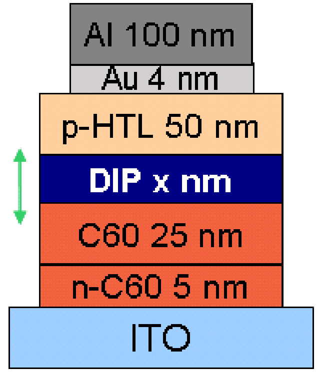
charge transfer/

charge generation

charge transport

charge extraction

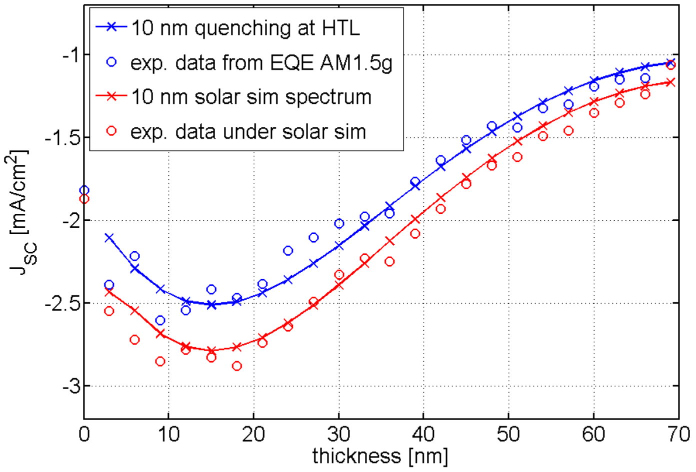
The exciton diffusion length problem



- Exciton diffusion lengths are rather small: ≈ 10 nm

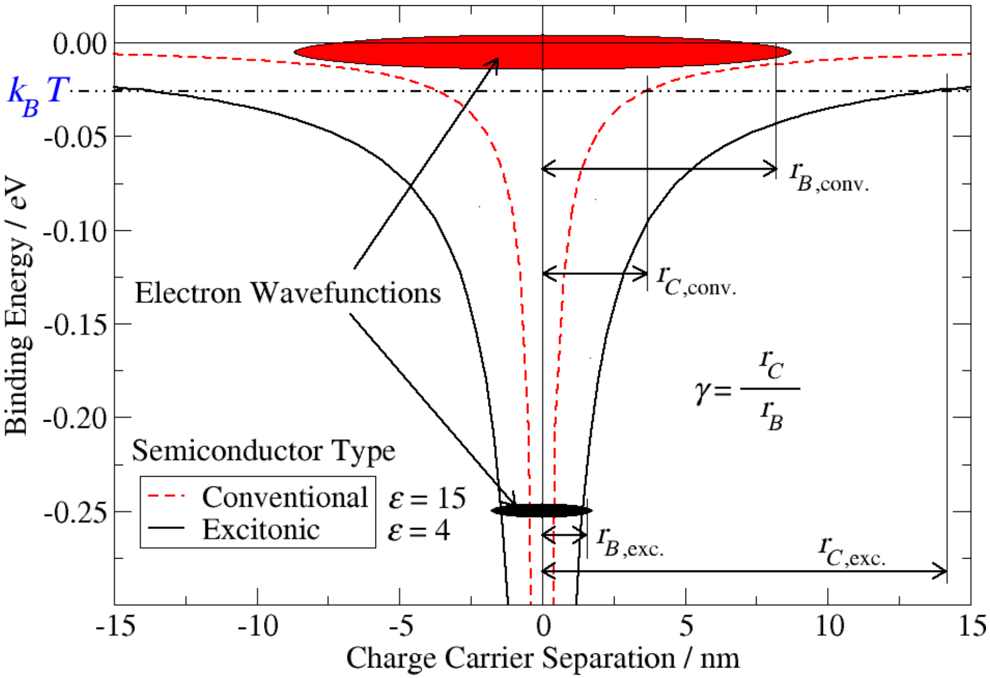
- Much higher values have been reported for materials with higher order

- Possible workaround: use triplet diffusion: so far not successful



Exciton diffusion length $L_D = (10 \pm 1)$ nm

The organic exciton separation problem



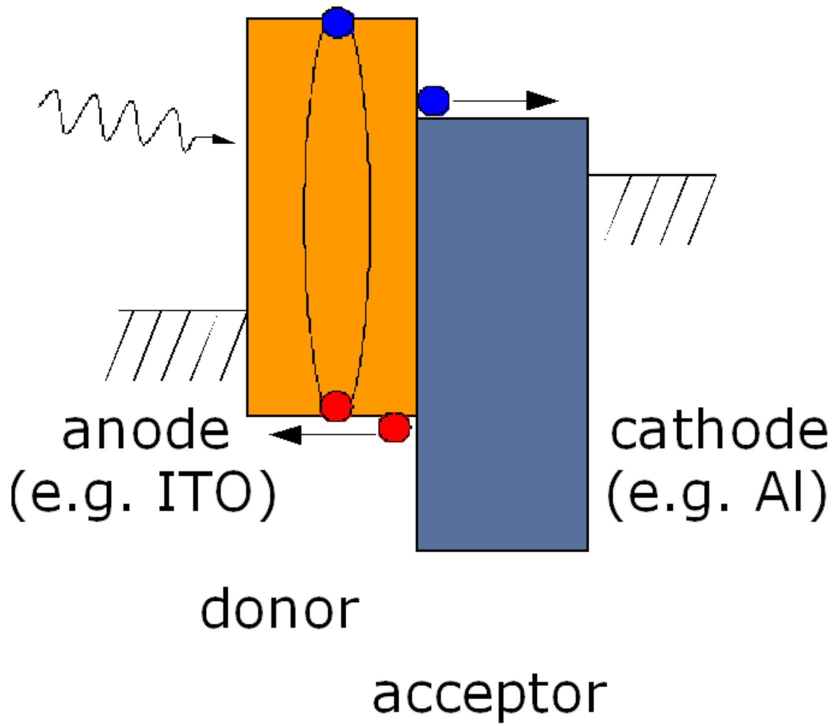
- Absorption leads to tightly bound (0.2 … 0.5 eV) excitons
- Separation in electric field inefficient
- Usual solar cell structure does not work

S. E. Gledhill et al. J. Mat Res. 20, 3167 (2005)

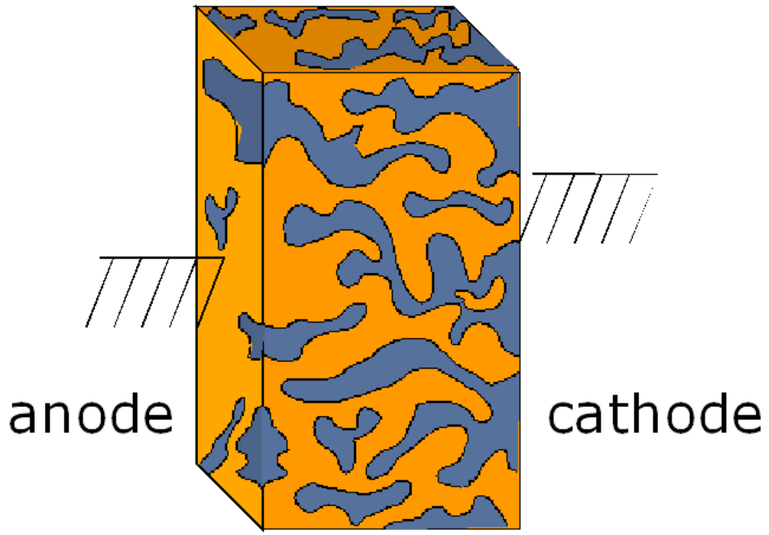
P. Würfel, CHIMIA 61, 770 (2007)

Exciton separation at a heterojunction

Flat heterojunction (FHJ)



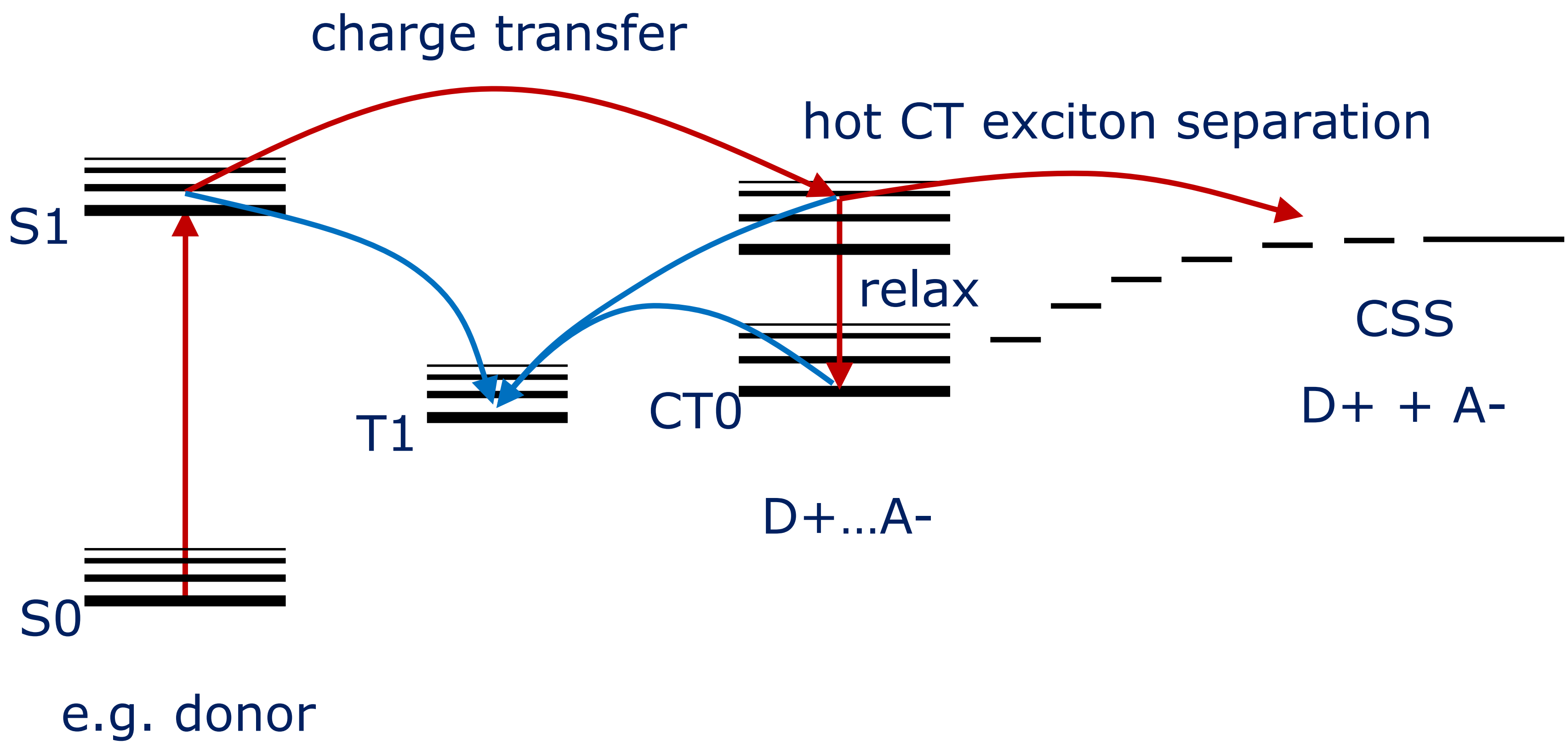
bulk heterojunction (BHJ)



Energy loss is unavoidable!

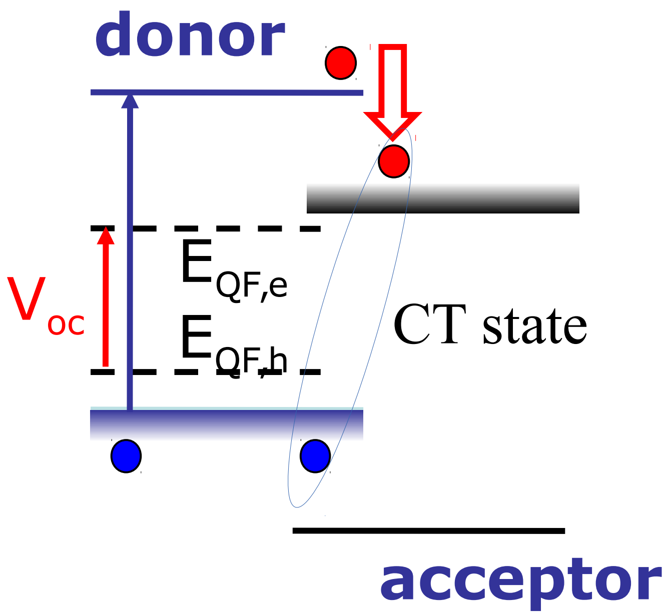
C. W. Tang, Appl. Phys. Lett. 48, 183 (1986)
M. Hiramoto et al., Appl. Phys. Lett. 58, 1062 (1991)
J. J. Hall et al., Nature 376, 498 (1995)
G. Yu et al. Science 270, 1789 (1995)

Exciton separation process



Which factors are promoting CT separation?

Origin of open circuit voltage



- Open circuit voltage is determined by quasi-Fermi level splitting
- Related to E_{CT}
- Ultimate limit not known

K. Vandewal et al., Nat. Mater. 8, 904 (2009)
K. Vandewal et al., Advanced Functional Materials 22, 3480–3490 (2012)
D. Veldman et al., Advanced Functional Materials 19, 1939 (2009)

High-efficiency polymer cells

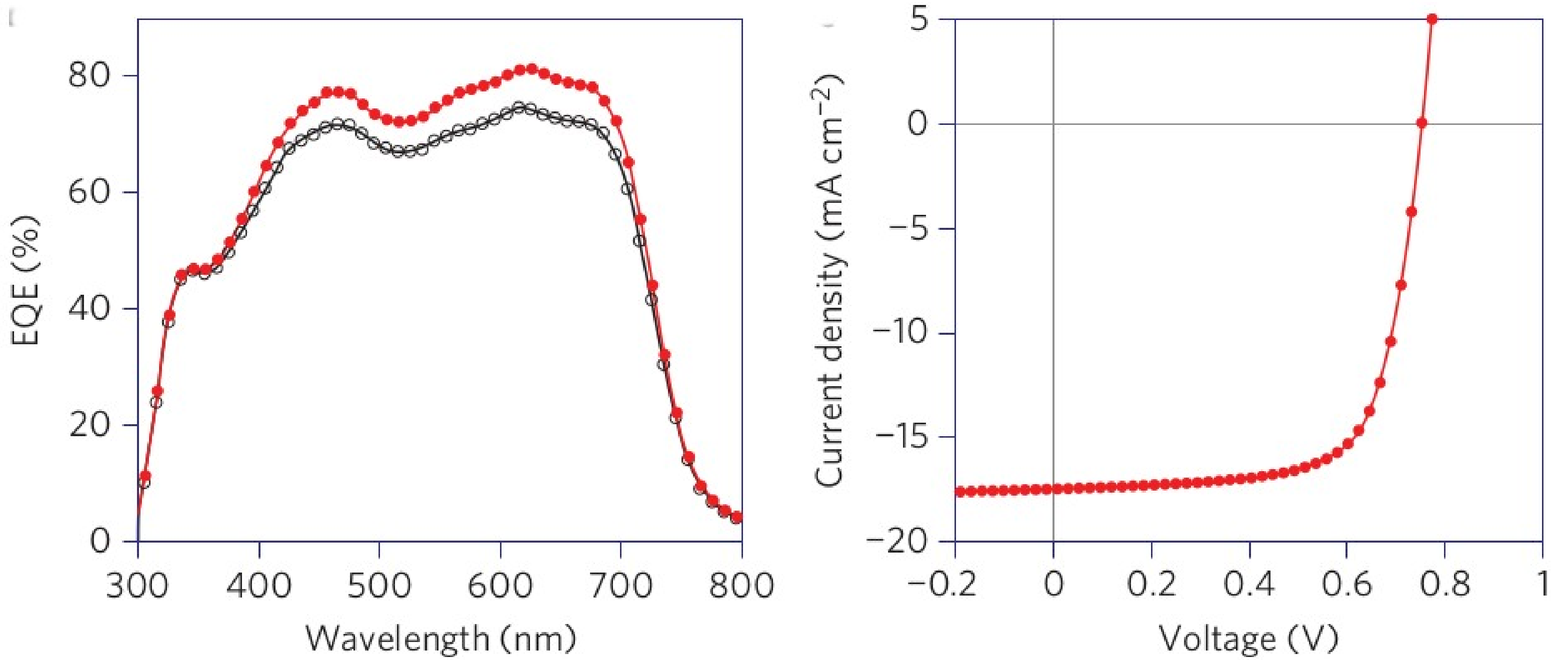


Table 1 | Best device performance/parameters from PTB7:$PC_{71}BM$ solar cells with conventional and inverted device structures, measured under 1,000 W m^{-2} AM 1.5G illumination.

Device type	PCE (%)	J_{SC} (mA cm^{-2})	FF (%)	V_{OC} (V)
Conventional	8.24	15.4	70.6	0.759
Inverted	9.15	17.2	72.0	0.740
Inverted, tested by CPVT	9.214	17.46	69.99	0.754

Z. He et al., Nature Photonics **6**, 591 (2012)

Outline

- Motivation
- Basics of organic solar cells
- **Materials requirements for organic solar cells**
- Exploring the thiophene zoo
- Tandem organic cells
- Lifetime&Manufacturing

Requirements for Bulk Heterojunction Materials

- Donor and acceptor must form network with high and balanced mobilities in both phases

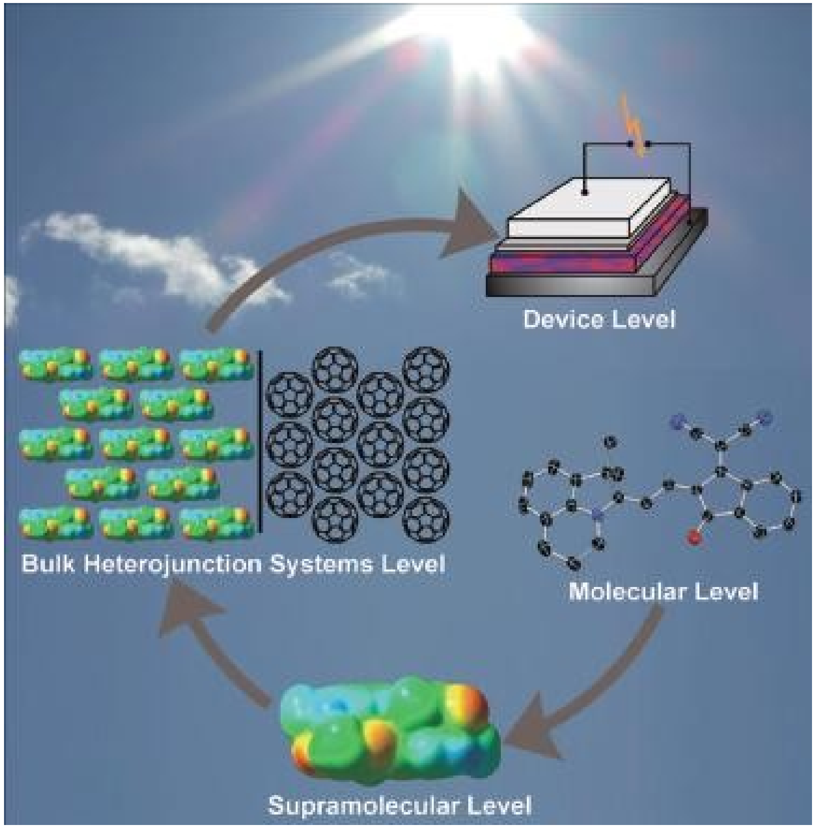
- Domain sizes must be adjusted to guarantee exciton separation and charge carrier transport

- Typically, mobilities of about 10^{-3} cm^2/Vs are needed

M. Mandoc et al., Appl. Phys. Lett. 90, 133504 (2007); Y.-X. Wang et al., Appl. Phys. Lett. 93, 133501 (2008), J.-T. Shieh et al., J. Appl. Phys. 107, 084503 (2010); A. Wagenpfahl et al., IEEE J. Sel. Top. Quantum Electron. 16, 1759 (2010); T. Kirchartz et al., Phys. Rev. B 80, 035334 (2009)

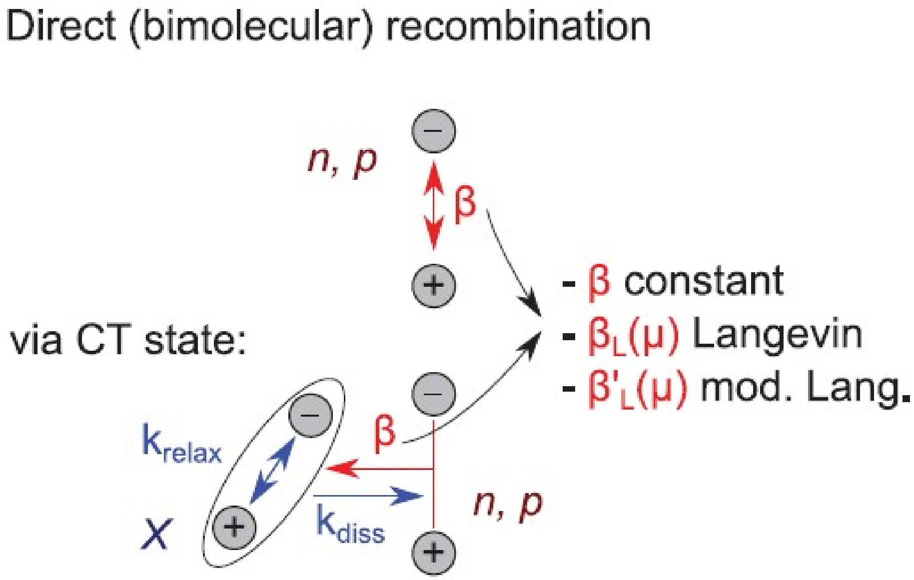
How to find the right molecule and morphology?

- Multi-scale approach needed for materials development
- Connection between molecular structure and device performance very complex

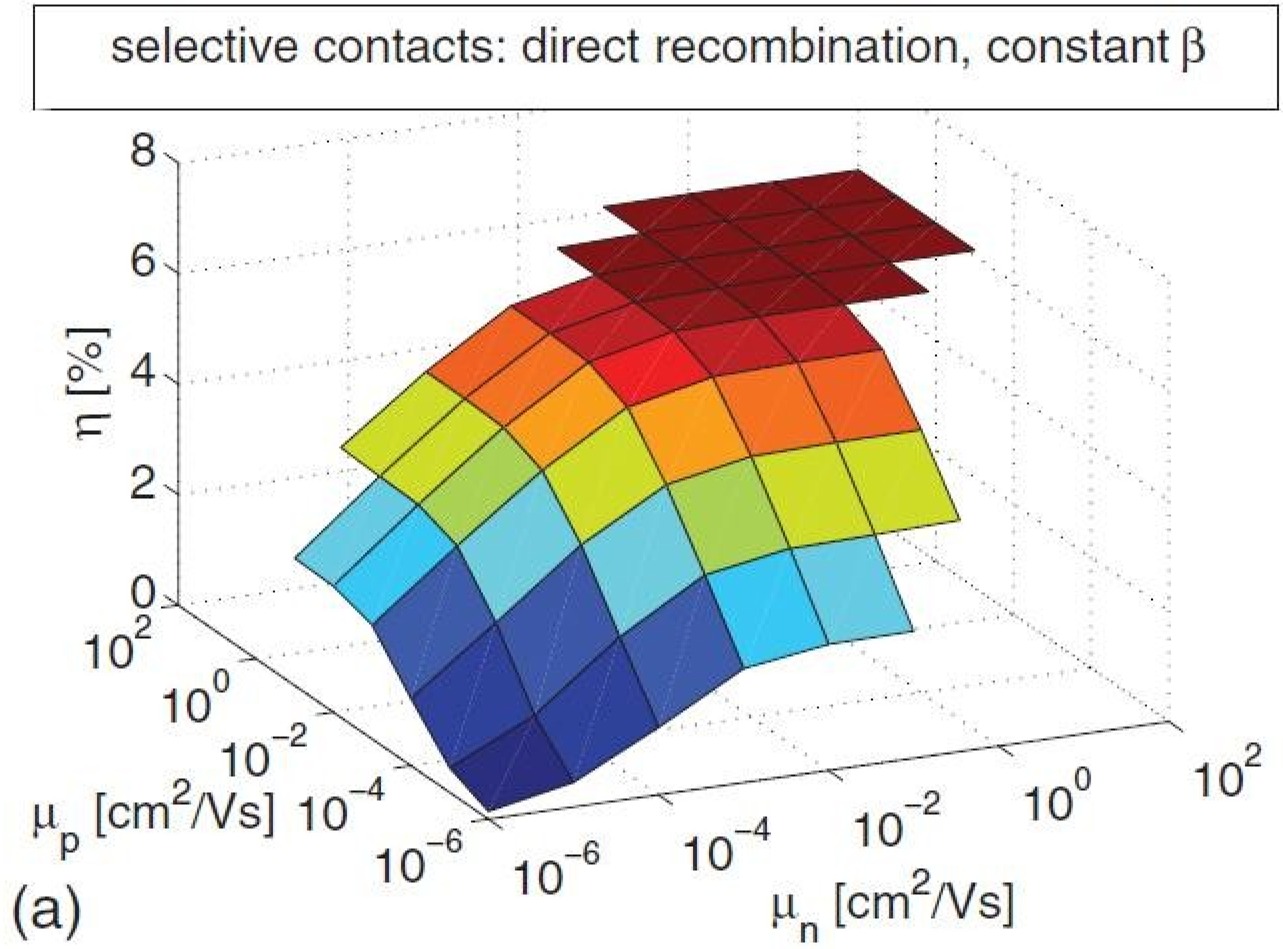


What are optimum mobilities?

- Drift-diffusion model set up by Wolfgang Tress
- Bulk Heterojunction between two contacts
- Different recombination models studied

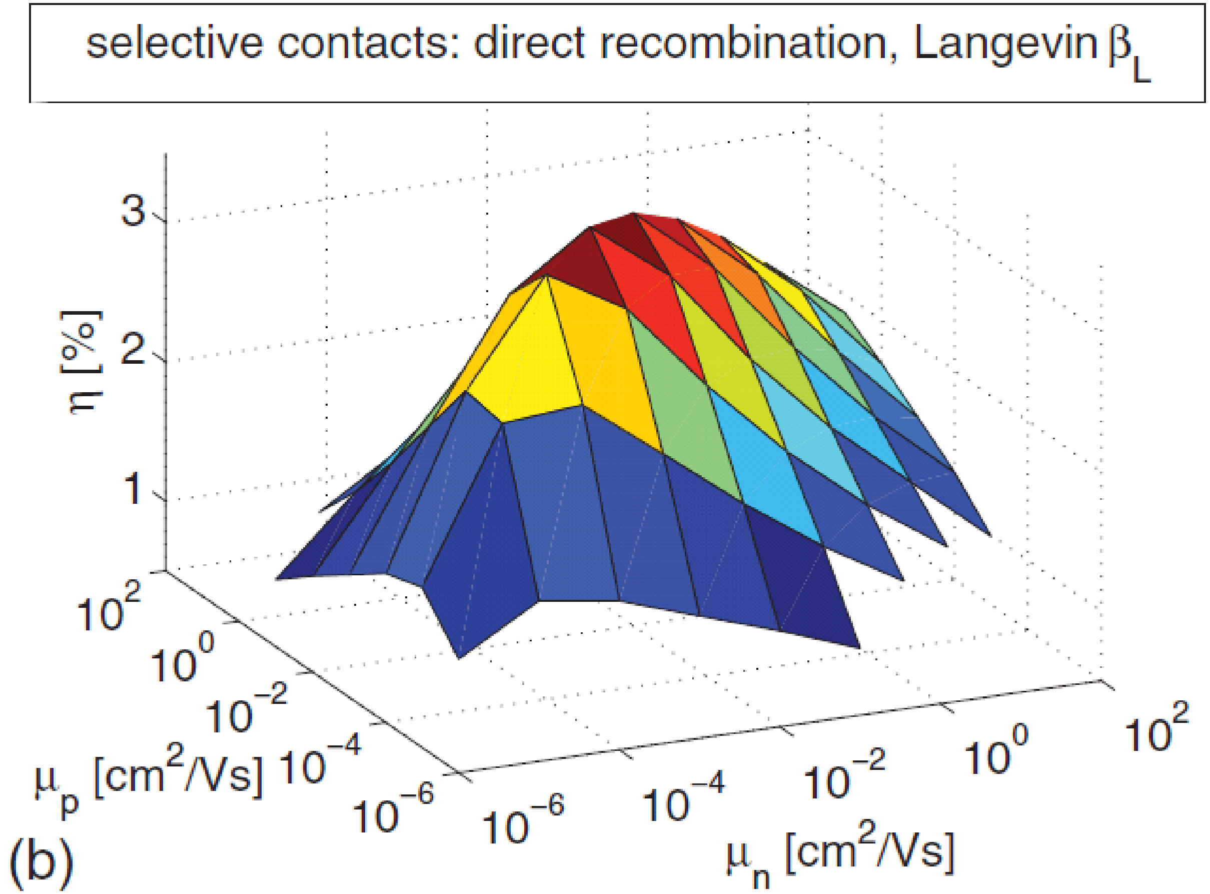


Direct recombination, without Langevin mechanism



W. Tress et al., Phys. Rev. **B** 85, 155201 (2012)

Direct recombination, with Langevin mechanism



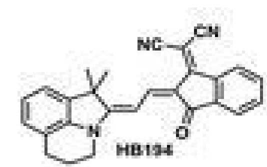
W. Tress et al., Phys. Rev. **B** 85, 155201 (2012)

New Small Molecule Absorber Materials

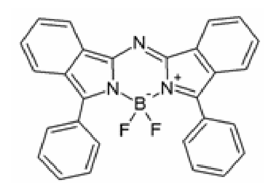
- Benzoporphyrins: Y. Matsuo et al., J. Am. Chem. Soc. **131**, 16048 (2009)

- Squaraines: F. Silvestri et al, J. Am. Chem. Soc. **130**, 17640 (2008); G. Wei et al., ACS Nano **4**, 1927 (2010)

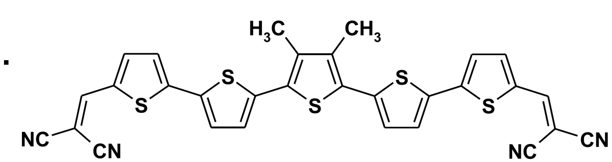
- Merocyanines: N. Kronenberg et al., J. Photon. Energy **1**, 011101 (2010)



- Bodipys: T. Rousseau et al., Chem. Comm. 1673 (2009), R. Gresser et al., Tetrahedron **67**, 7148 (2011)



- Thiophenes: K. Schulze et al., Adv. Mat. **18**, 2872 (2006); E. Ripaud et al., Adv. En. Mat. **1,** 540 (2011), Y. Sun et al., Nature Mat. **11**, 44 (2012) , Z. Li et al., Adv. En. Mat. **2**, 74 (2012), J. Zhou et al., JACS **134**, 16345 (2012)



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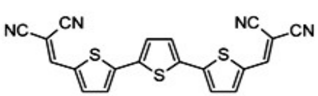
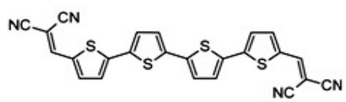
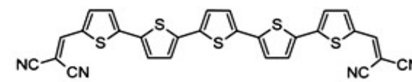
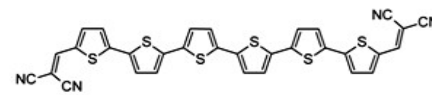
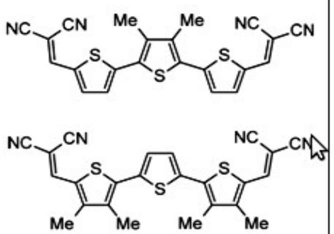
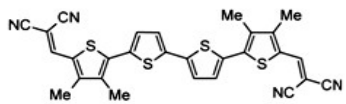
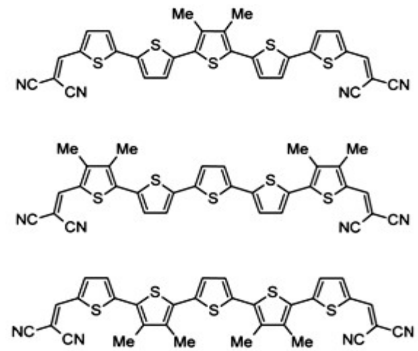
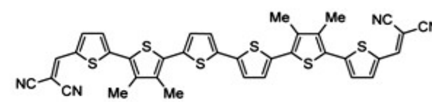
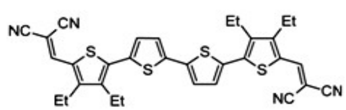
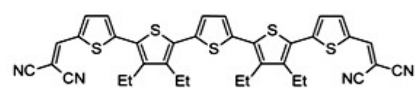
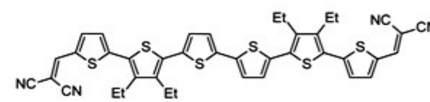
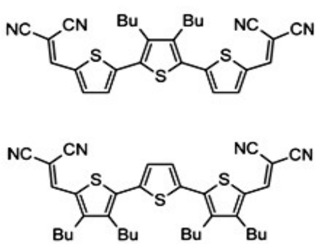
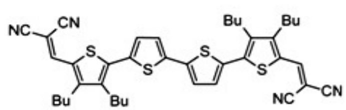
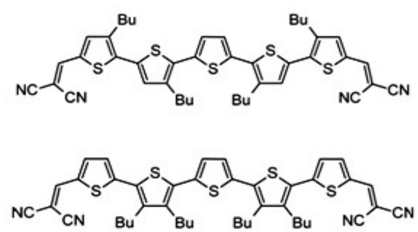
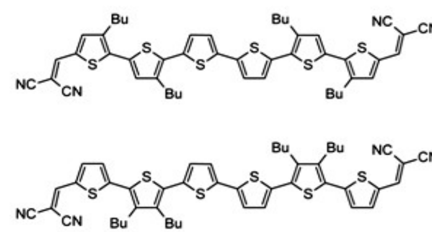
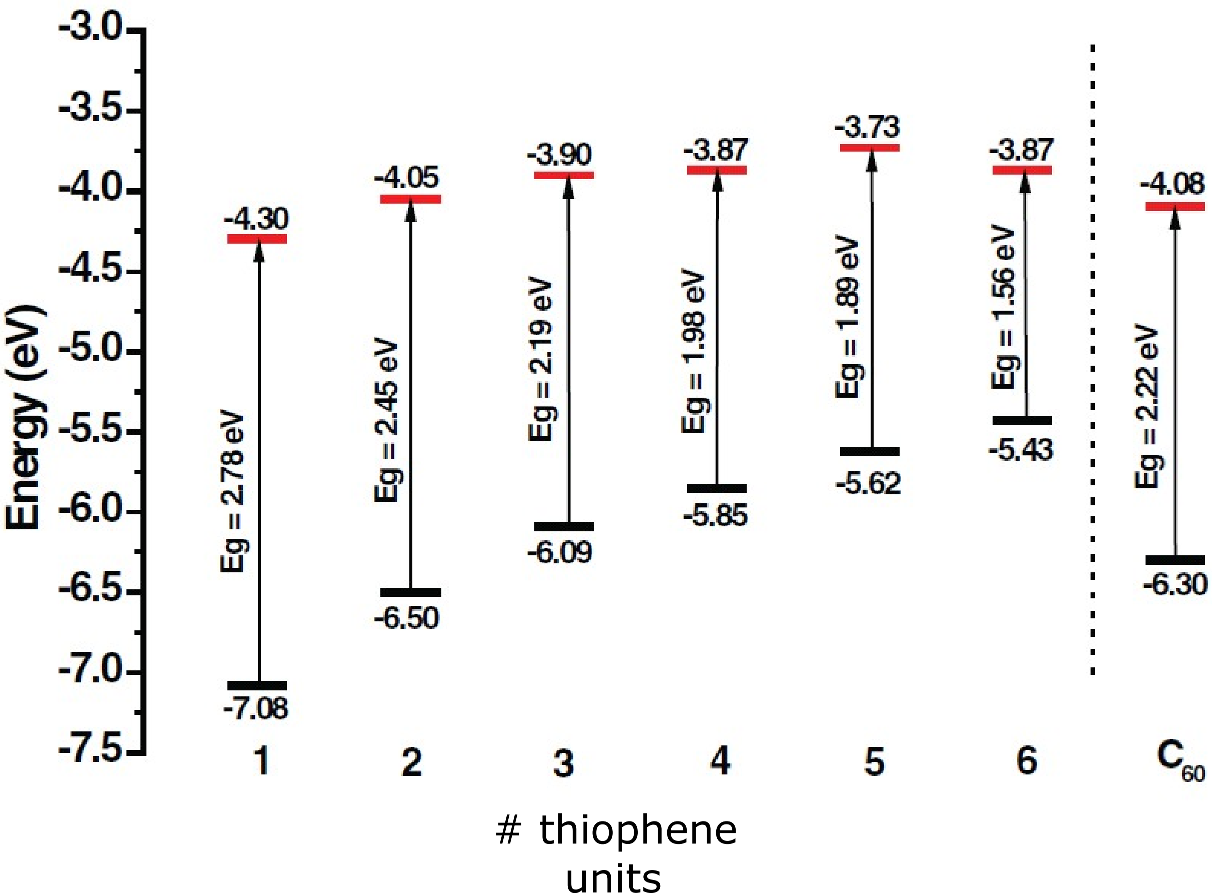
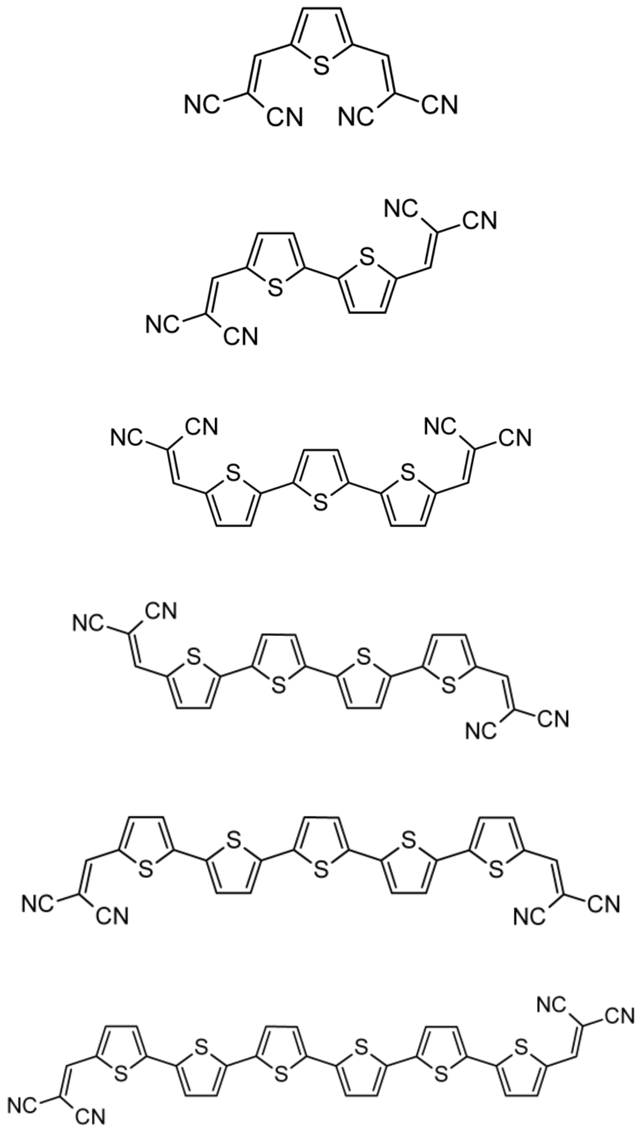
The thiophene zoo...

	3T	4T	5T	6T
H				
Me				
Et				
Bu				

Energy Levels vs. backbone length

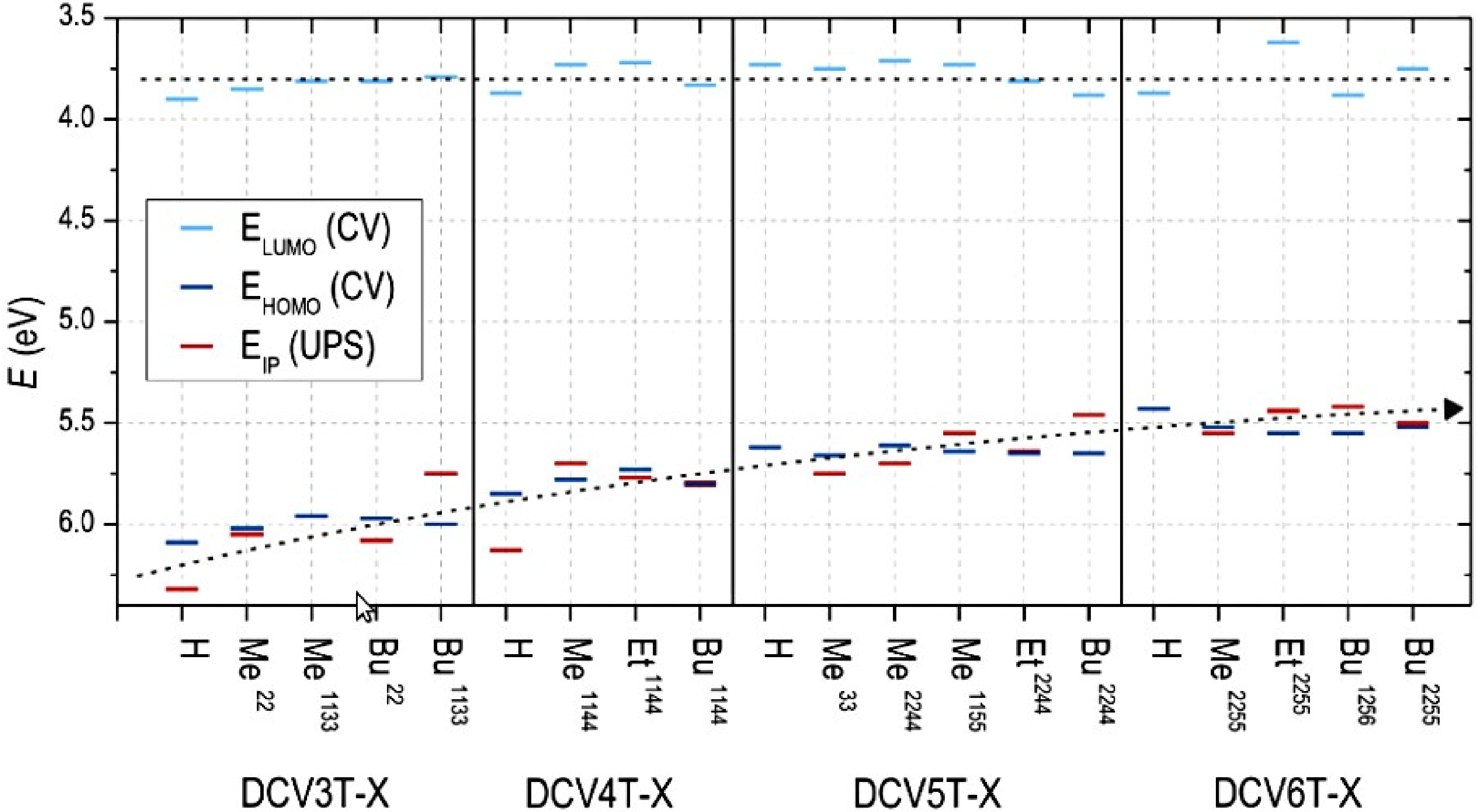




DCVnT: Fitzner et al., AFM 21, 897 (2011)

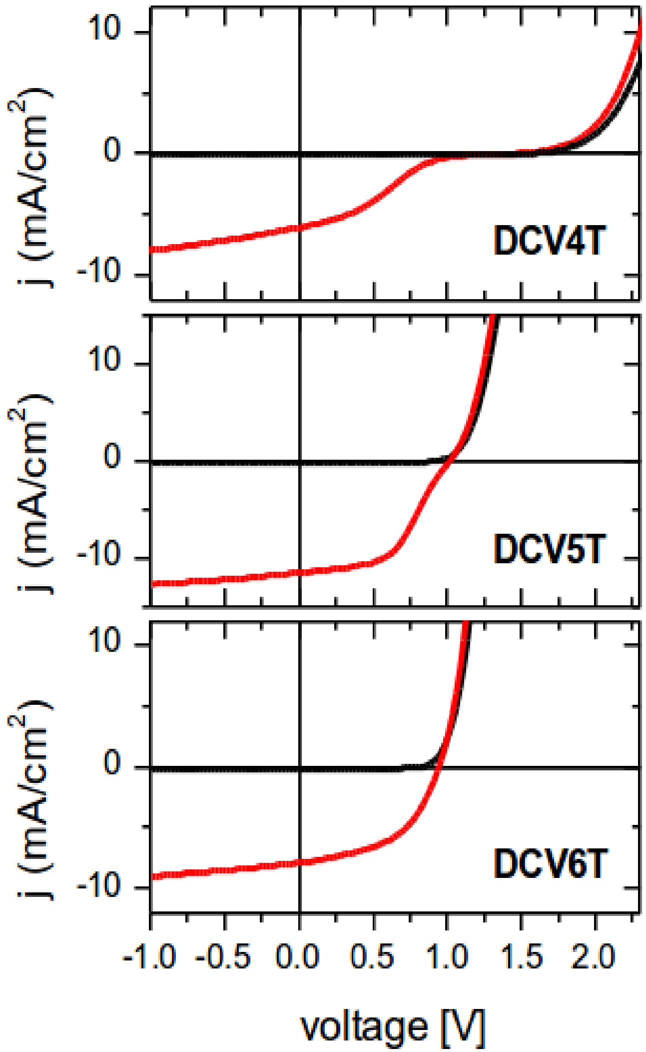
DCVnT-Bu: Schüppel et al., PRB 77, 085311 (2008)

Influence of side chains on energy levels



- Only weak effects of side chains in solution
- Stronger effects in thin films

Solar Cells with DCVnT



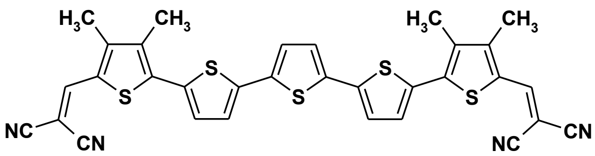
Open circuit voltage	Charge carrier separation efficiency fill factor FF saturation factor $j_{(-1V)}/j_{SC}$
V_{oc} = 1.13 V	FF = 27.6% $j_{(-1V)}/j_{sc}$ = 1.32
V_{oc} = 1.00 V	FF = 50.4% $j_{(-1V)}/j_{sc}$ = 1.10
V_{oc} = 0.93 V	FF = 49.7% $j_{(-1V)}/j_{sc}$ = 1.15
decreases	***increases***

with **increasing** chain length

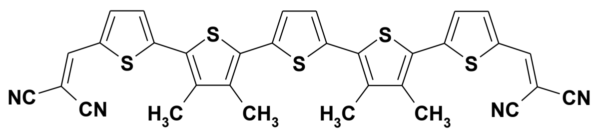
ITO / Au(1) / pTNATA(30) / pNPD(10,4:1) / NPD(5) / **DCVnT** (8) / **C_{60}** (40) / Bphen(6) / Al(100)

Minimum exciton separation loss is approx. 0.3eV

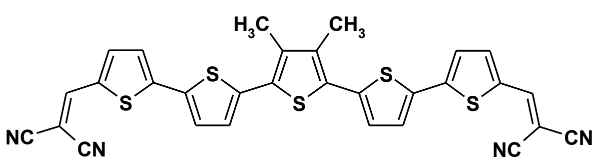
New Thiophenes: DCV5T-Me Series



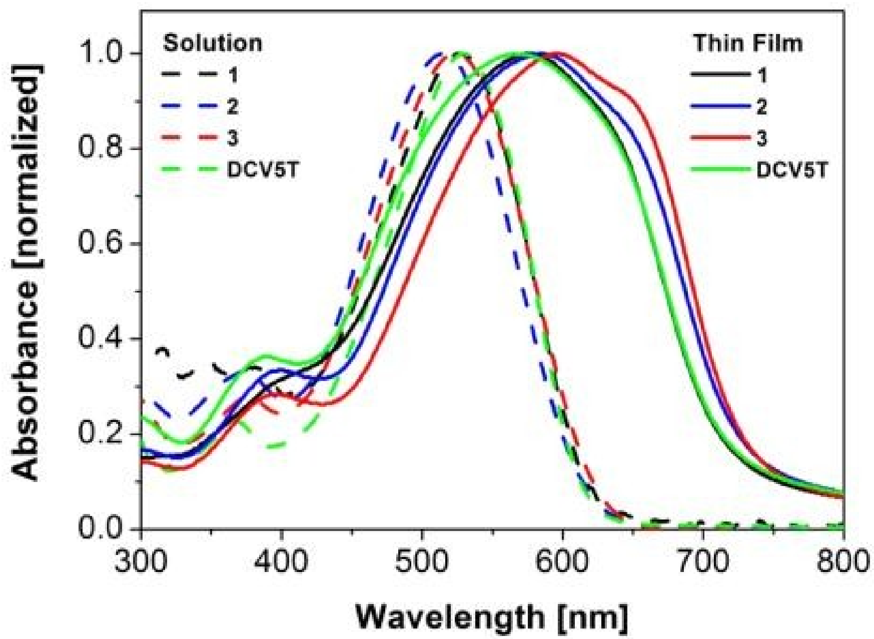
1: DCV5T-Me(1,1,5,5)



2: DCV5T-Me(2,2,4,4)



3: DCV5T-Me(3,3)



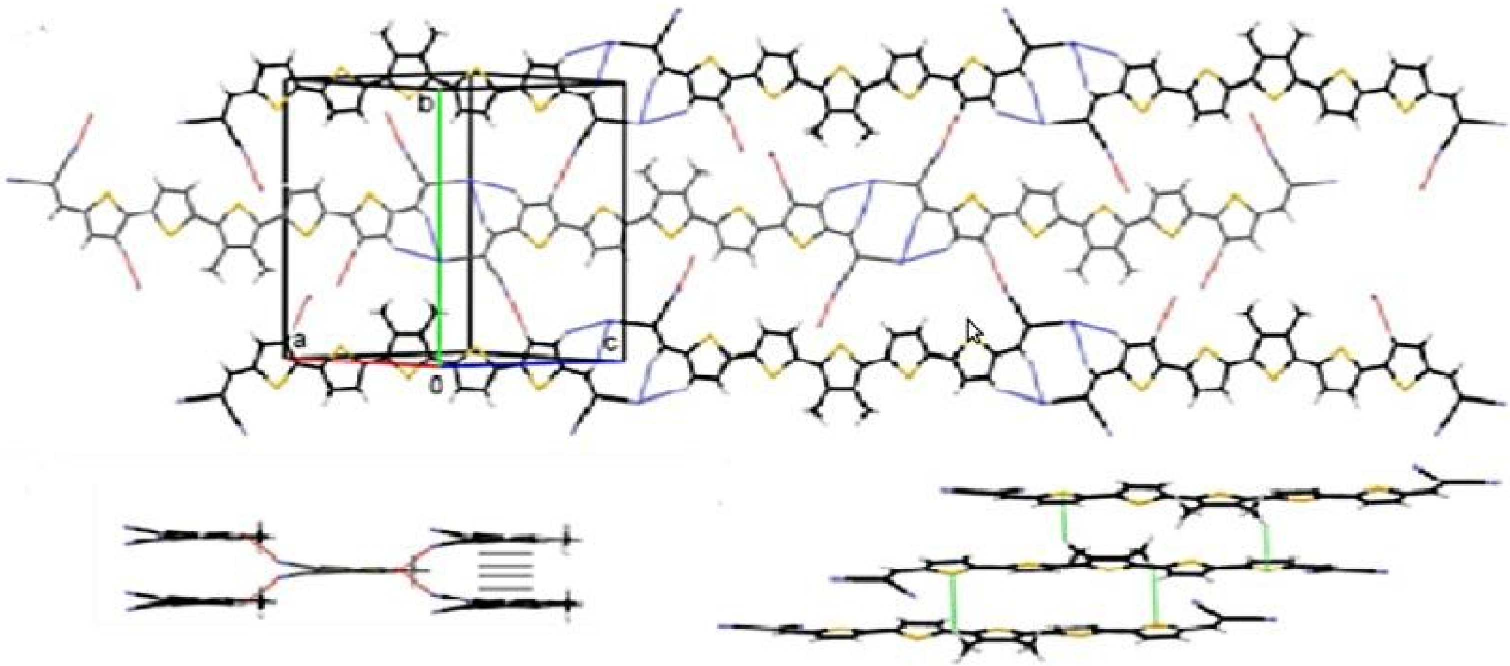
Heliatek

University of Ulm
Department Organic
Chemistry II

R. Fitzner *et al.*, JACS **134**, 11064 (2012)

New thiophenes: crystal structure

- 4 molecules/unit cell
- Very close π-π stacking of 3.28Å



Singe crystals from gradient sublimation
X-Ray analysis: M. Weil, Vienna

Dependence of Ordering on Substrate Temperature

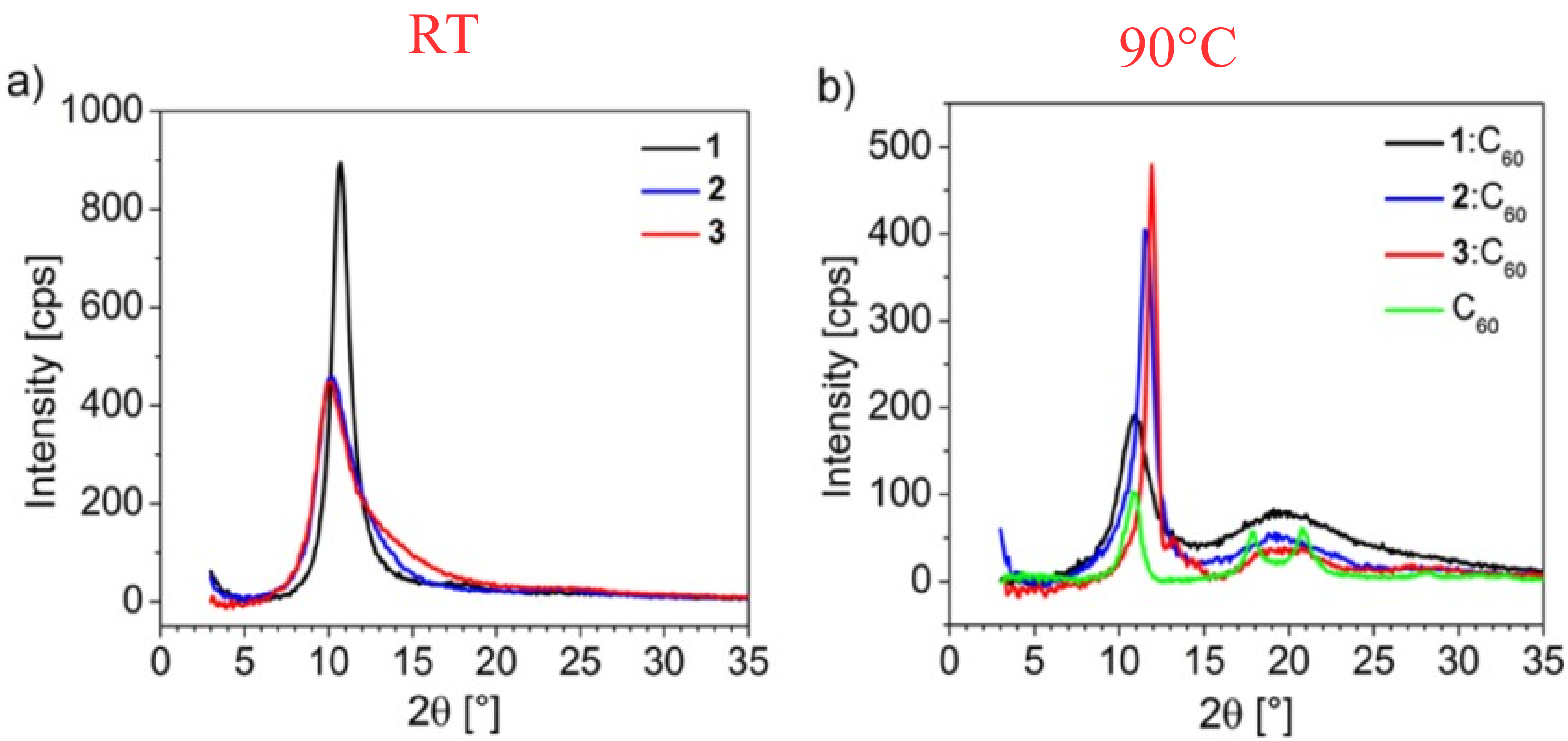
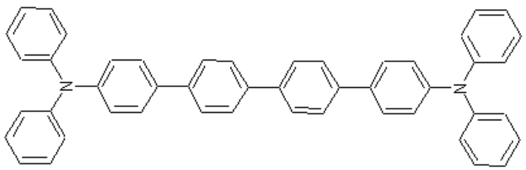


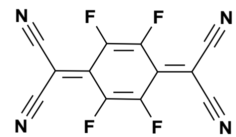
Figure 4. GIXRD patterns of (a) 50 nm films of neat **1−3** deposited on glass substrates at room temperature and (b) 75 nm **1−3**:C_{60} (2:1 v/v) blend layers fabricated by coevaporation on glass substrates at 90 °C, with the pattern for pristine C_{60} shown for comparison.

The p-i-n Concept for Organic Solar Cells

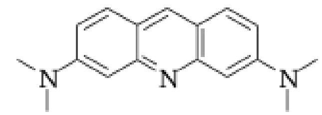


4P-TPD

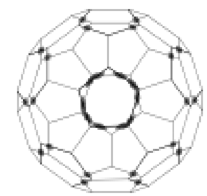
F4-TCNQ



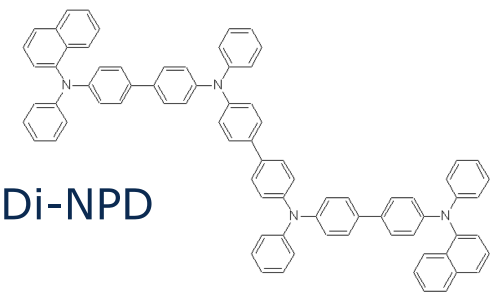
AOB

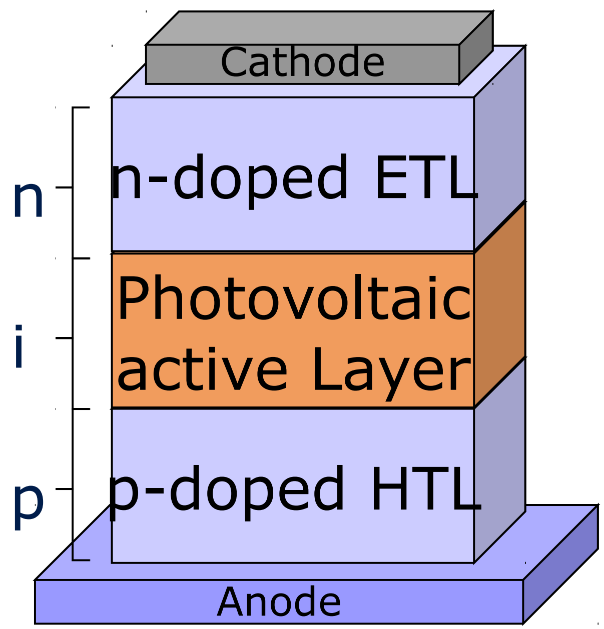


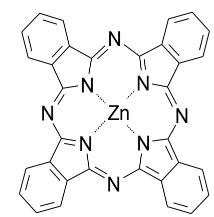
C60



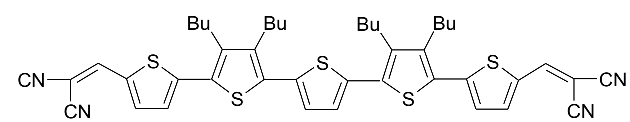
Di-NPD



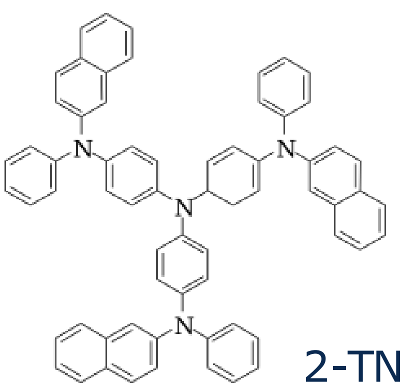




ZnPc



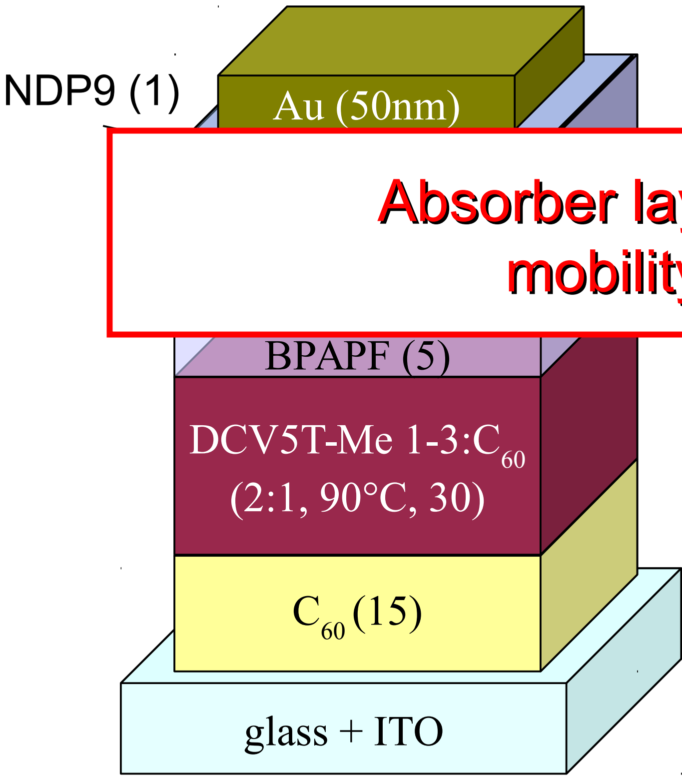
DCV5T-Bu

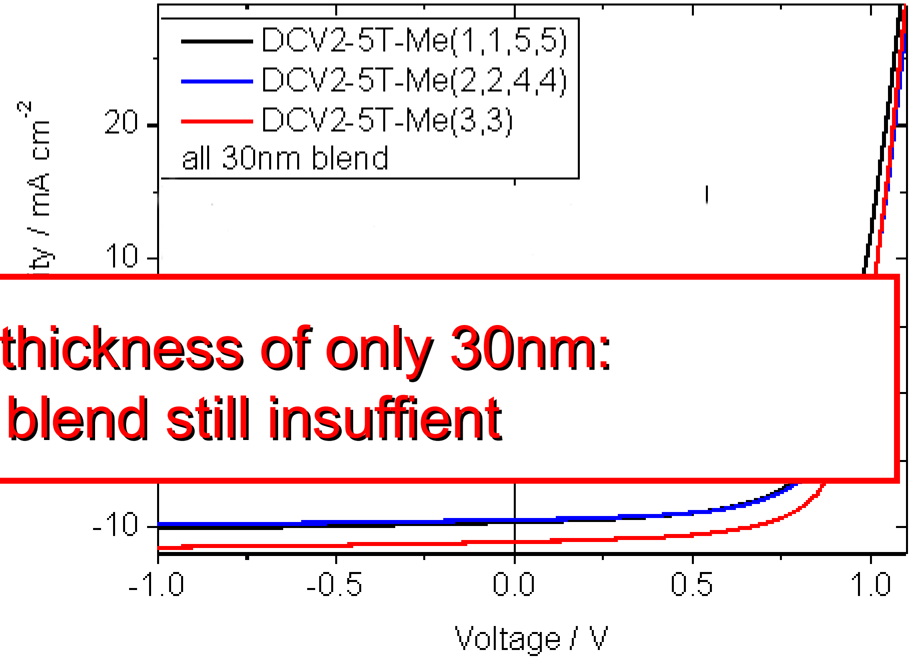


2-TNATA

B. Maennig *et al.*, Appl. Phys. A 79, 1 (2004)
M. Riede *et al.*, Nanotechnology 19, 424001 (2008)

DCV5T-Me Results





Absorber layer thickness of only 30nm: mobility in blend still insuffient

#	V_{OC} (V)	I_{SC} (mA/cm²)	FF	Eff.(%)
1	0.91	9.6	62.5	**5.5**
2	0.95	9.4	62.1	**5.6**
3	0.96	11.1	65.6	**6.9**

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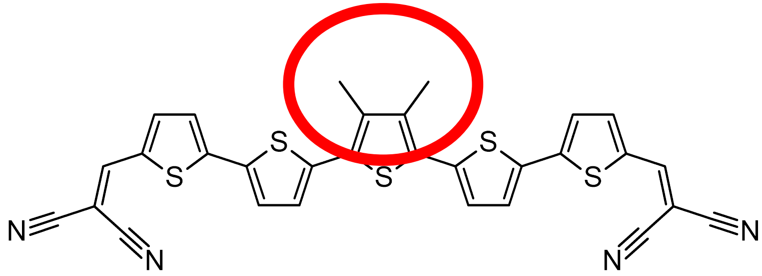
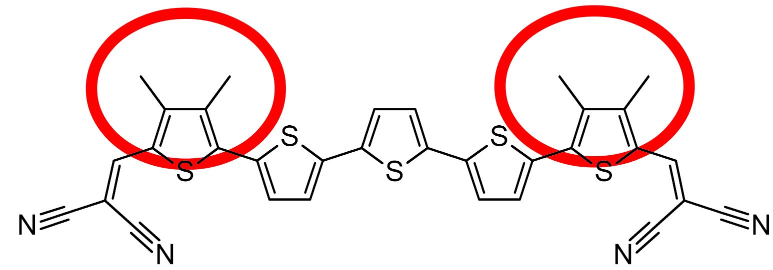
The DCV5T-Me story revisited...
(Chris Elschner et al.)



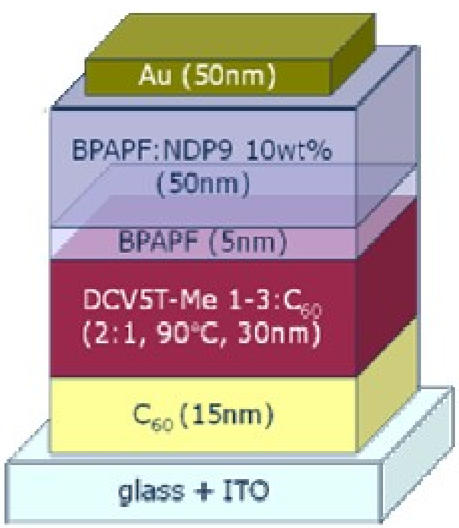
DCV5T-Me(3,3) **[D33]**

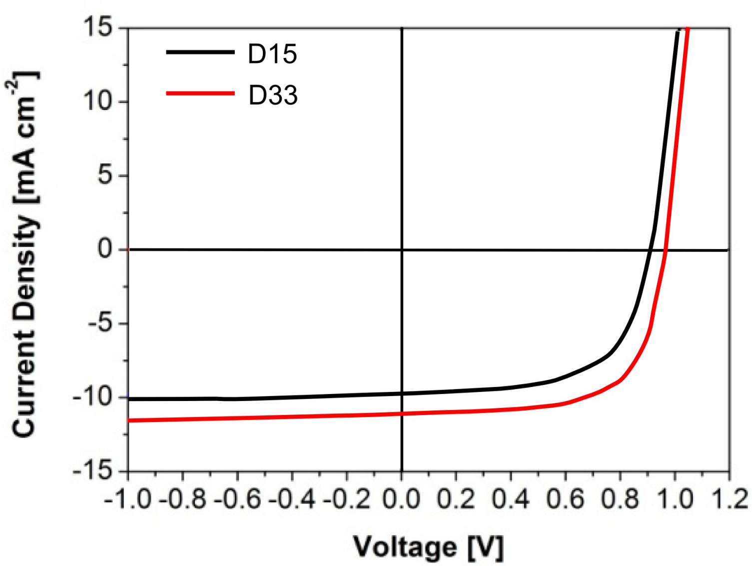
6.9%



DCV5T-Me(1,1,5,5) **[D15]**

4.8%

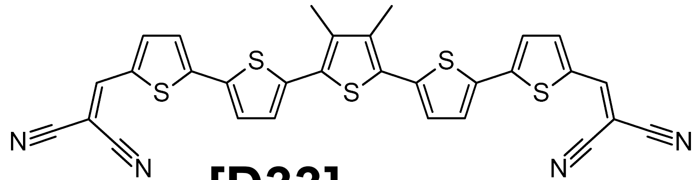




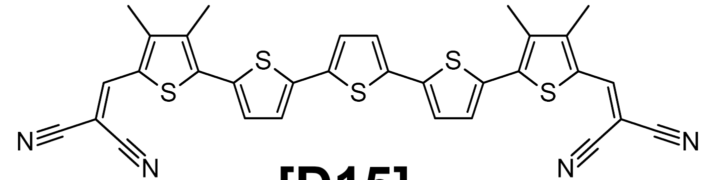
- almost identical molecular structure
- identical stack

TECHNISCHE UNIVERSITÄT DRESDEN

GIWAXS single layers glass / DCV5Ts (30 nm)



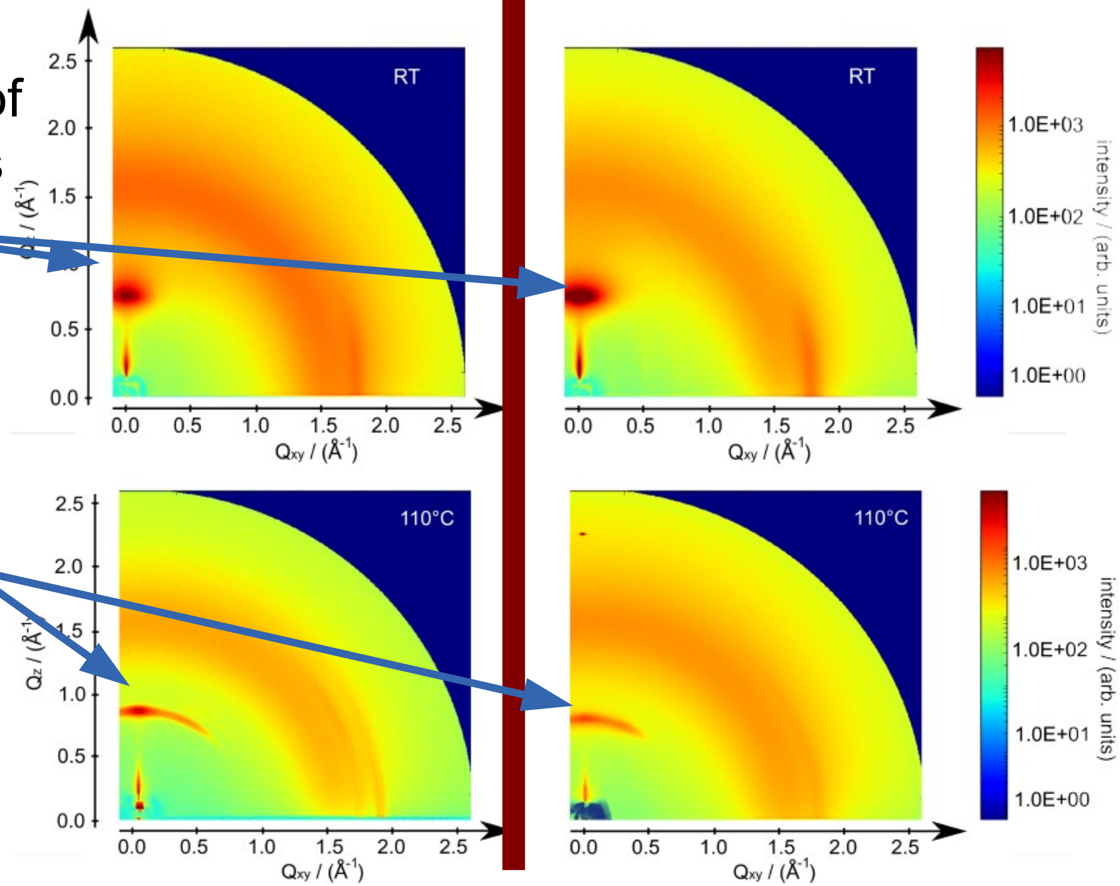
[D33]



[D15]

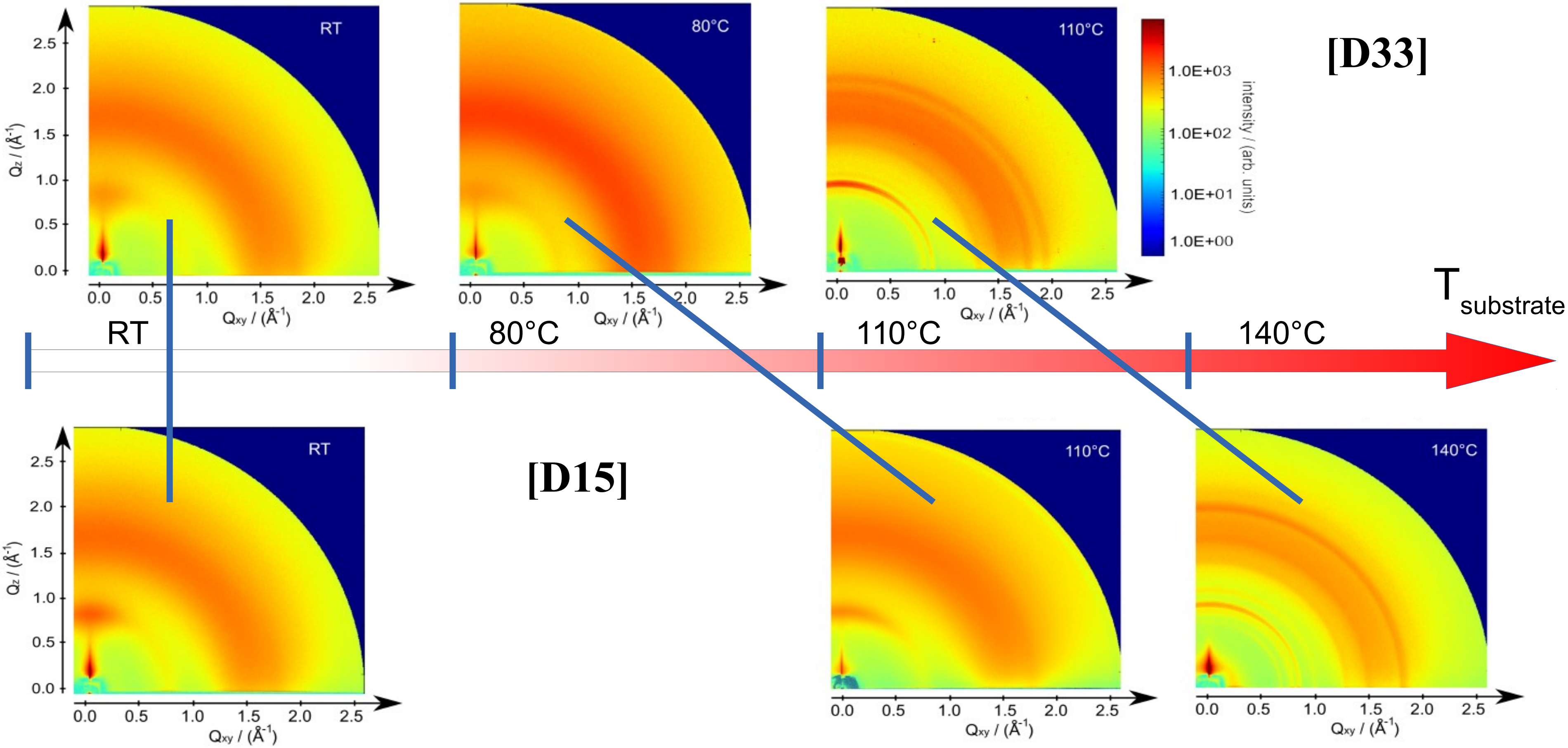
- broadened out of plane reflections @ RT

- orientation of crystals spreads out, crystal size grows @ 110°C



single layer pattern very similar !

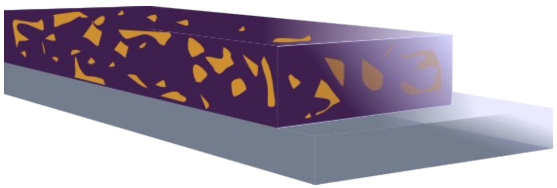
GIWAXS blends
glass / DCV5Ts : C60 (30 nm, 2:1)



D33 (top): best OSC @80°C, crystallization @110°C

D15 (bottom): best OSC @≈110°C (?), crystallization @140°C

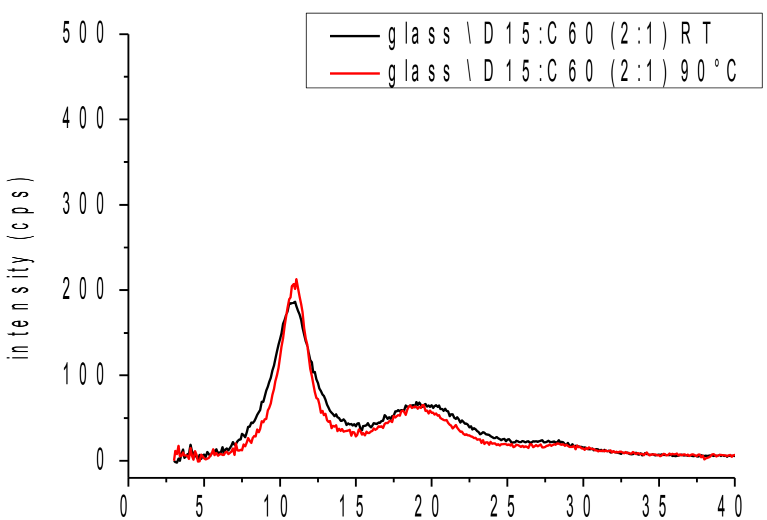
Interpretation



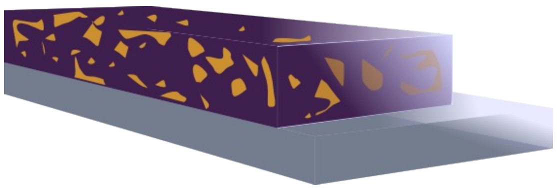
$T_{substrate}$

RT intermediate temp. high temp.

- nanoscale mixing of donor and C60
- low crystallinity
- smooth surface



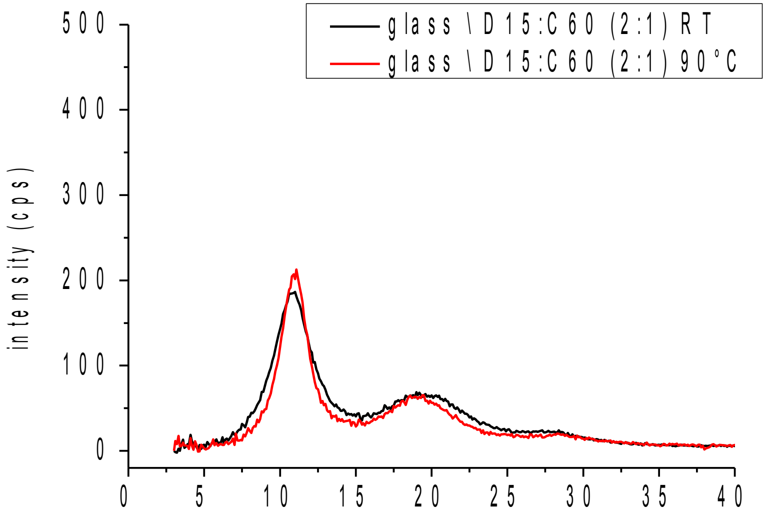
Interpretation



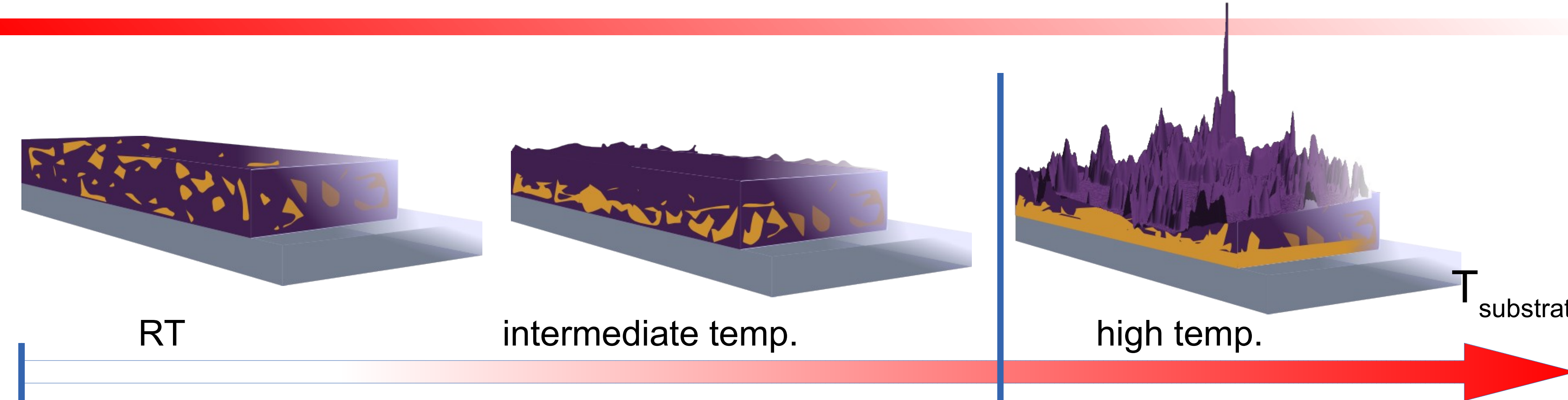
RT intermediate temp. high temp. $T_{substrate}$

- nanoscale mixing of donor and C60
- low crystallinity
- smooth surface

- morphology changes:
  - crystallinity
  - roughness
  - OSC efficiency



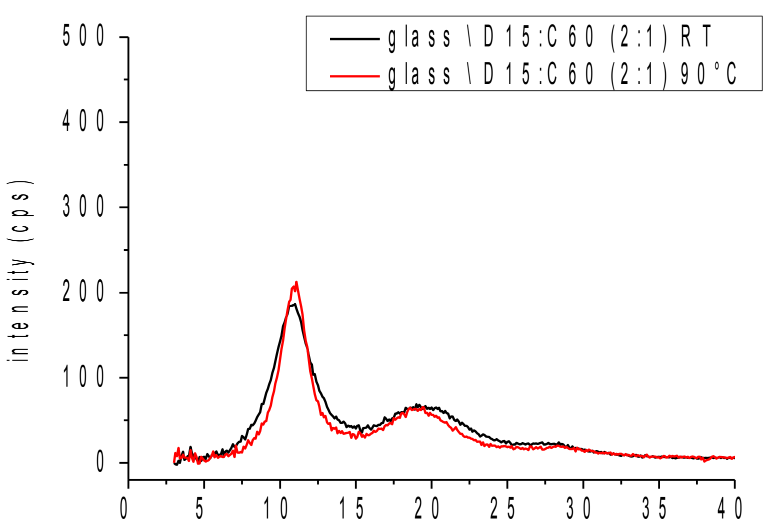
Interpretation



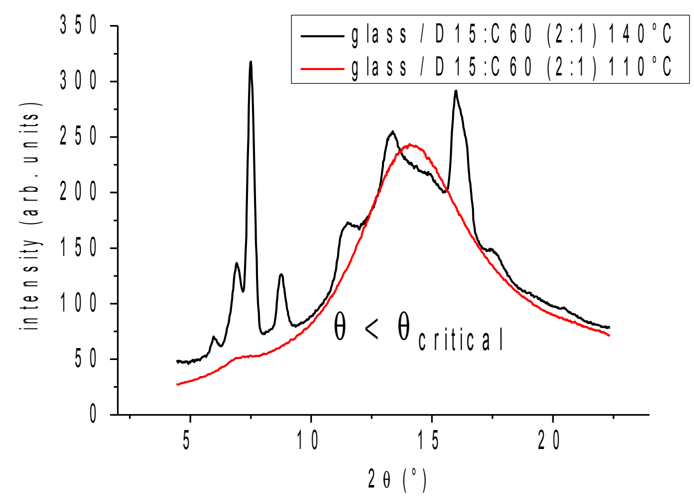
- nanoscale mixing of donor and C60
- low crystallinity
- smooth surface

- morphology changes:
  - crystallinity →
  - roughness ↑
  - OSC efficiency ↑

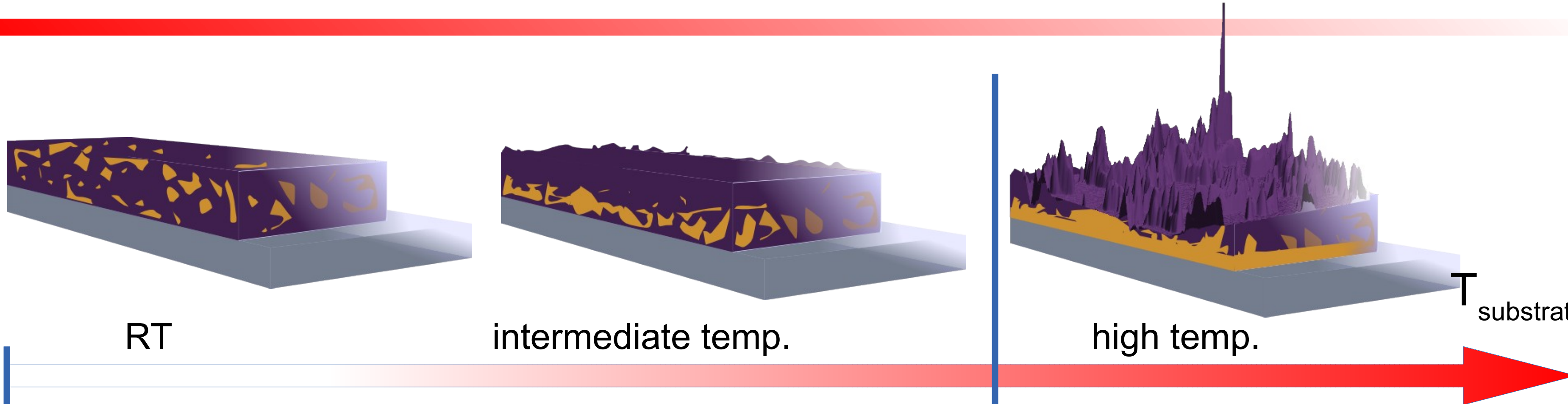
- surface segregation of DCV → crystallinity ↑
  → roughness ↑
- OSC efficiency ↓



[D15] > **110°C**
[D33] > **80°C**



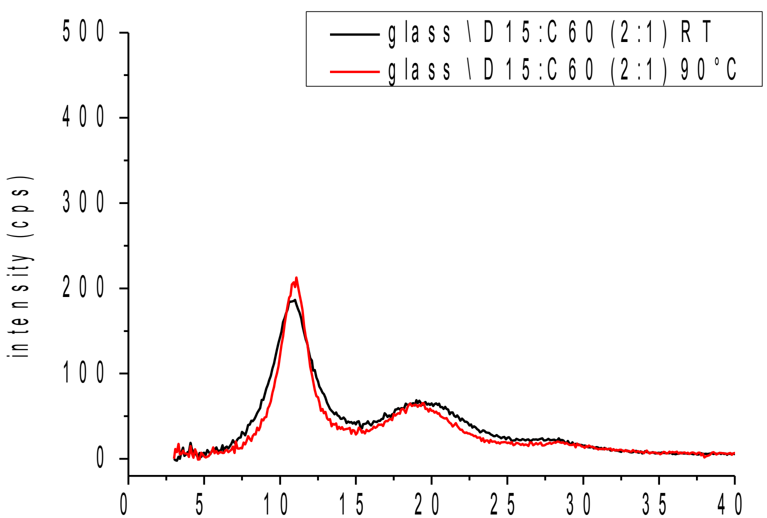
Interpretation



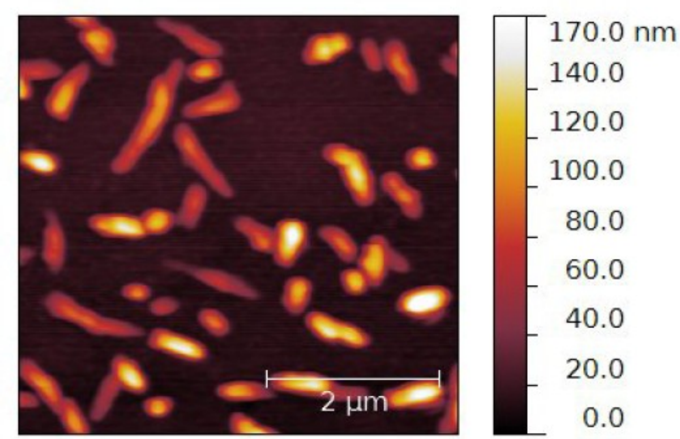
- nanoscale mixing of donor and C60
- low crystallinity
- smooth surface

- morphology changes:
  - crystallinity
  - roughness
  - OSC efficiency

- surface segregation of DCV → crystallinity
  → roughness
- OSC efficiency



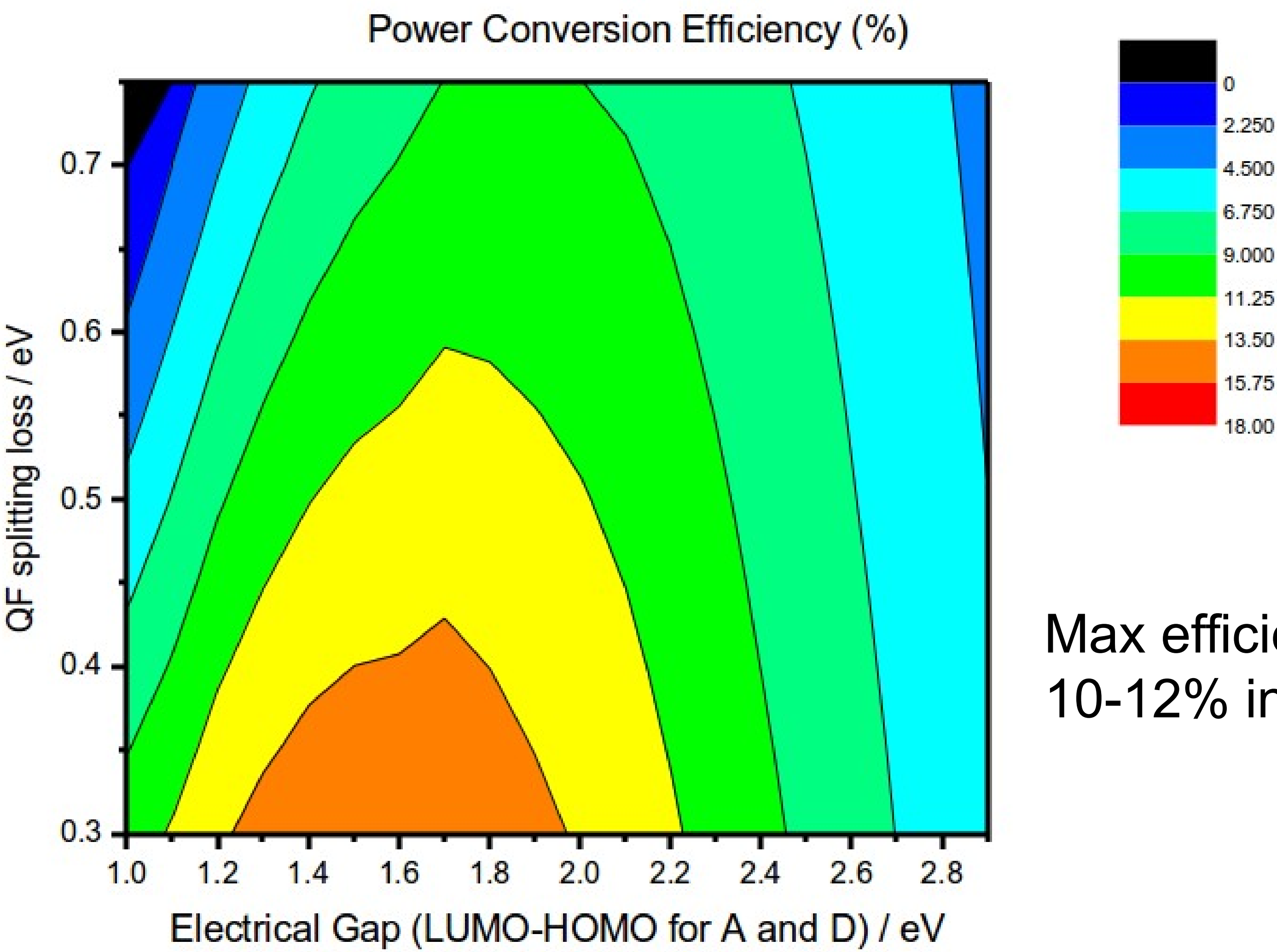
[D15] > **110°C**
[D33] > **80°C**



Outline

- Motivation
- Basics of organic solar cells
- Materials requirements for organic solar cells
- Exploring the thiophene zoo
- **Tandem organic cells**
- Lifetime&Manufacturing

Efficiency Outlook Single Cells



Main assumptions:

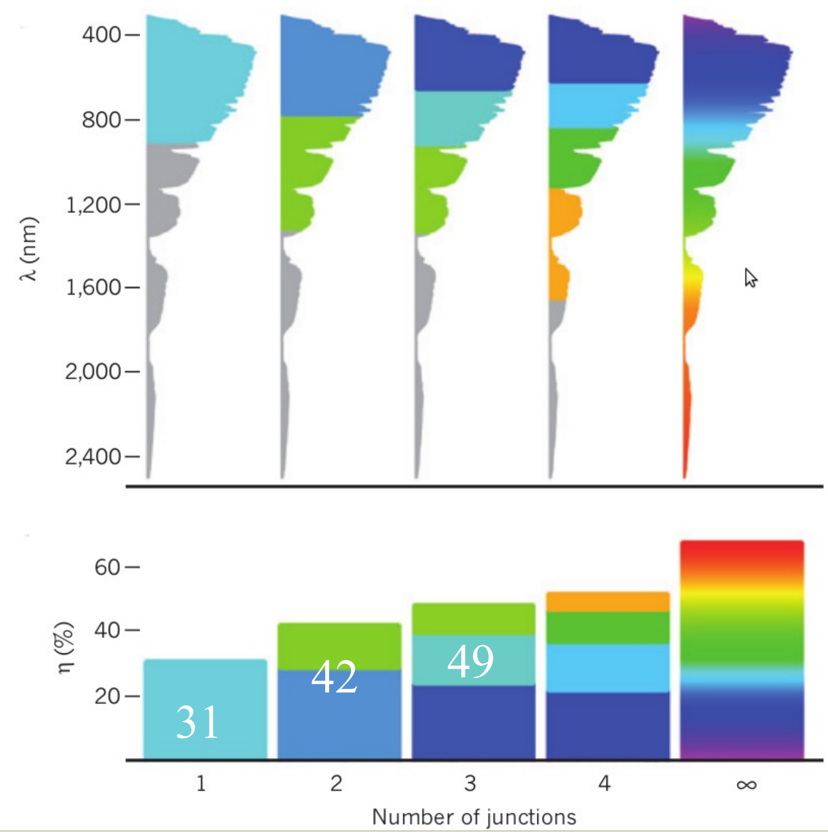
- EQE 60%
- FF 60%

Max efficiency about 15%:
10-12% in module

T. Mueller et al.

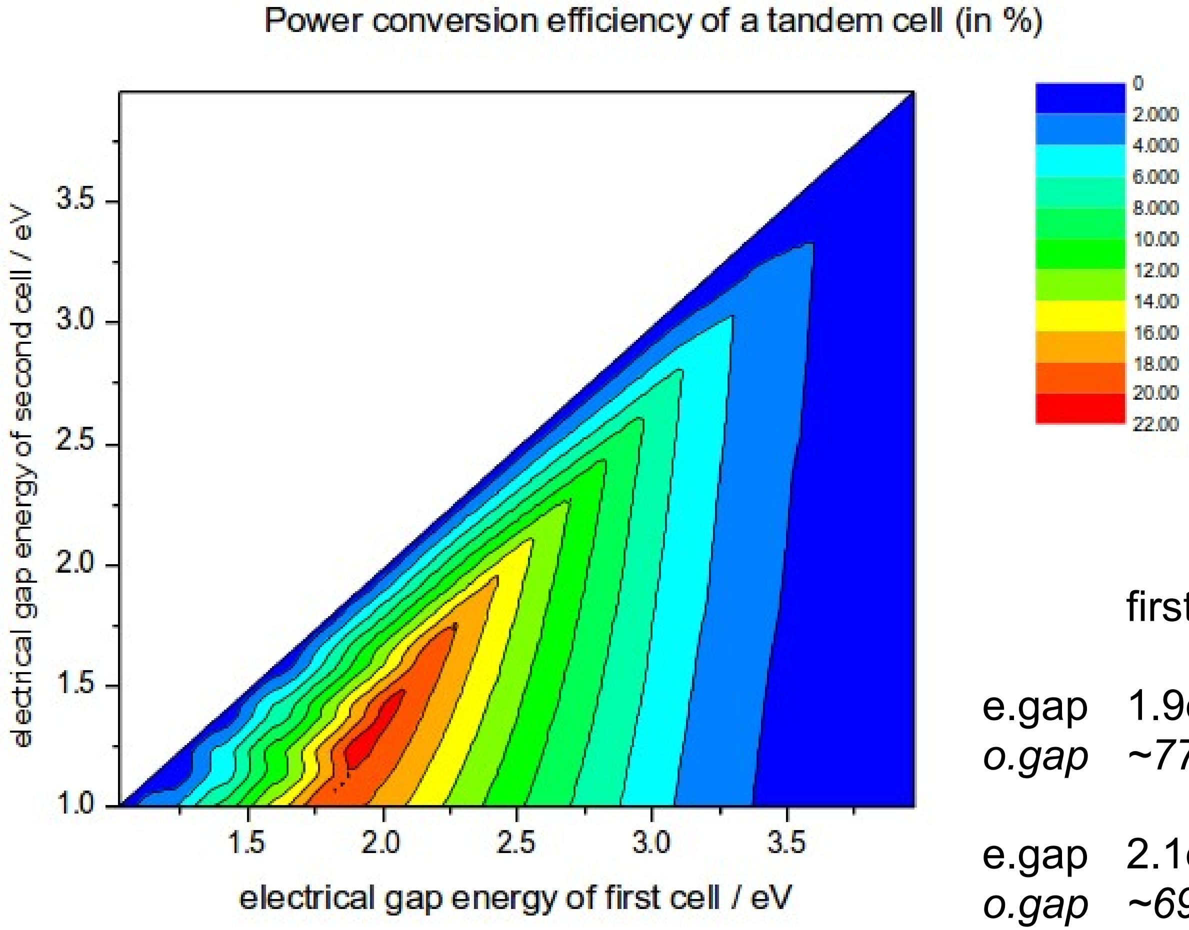
Higher Efficiency for Multijunction Cells

- Shockley-Queisser limit for single junction: 31%
- Major gains only for
  - Tandem junction: 42%
  - Triple junction: 49%
- Lower currents/higher voltages reduce electrical losses



M. Graetzel et al., Nature **488**, 304 (2012)

Efficiency Outlook for Tandem Cells



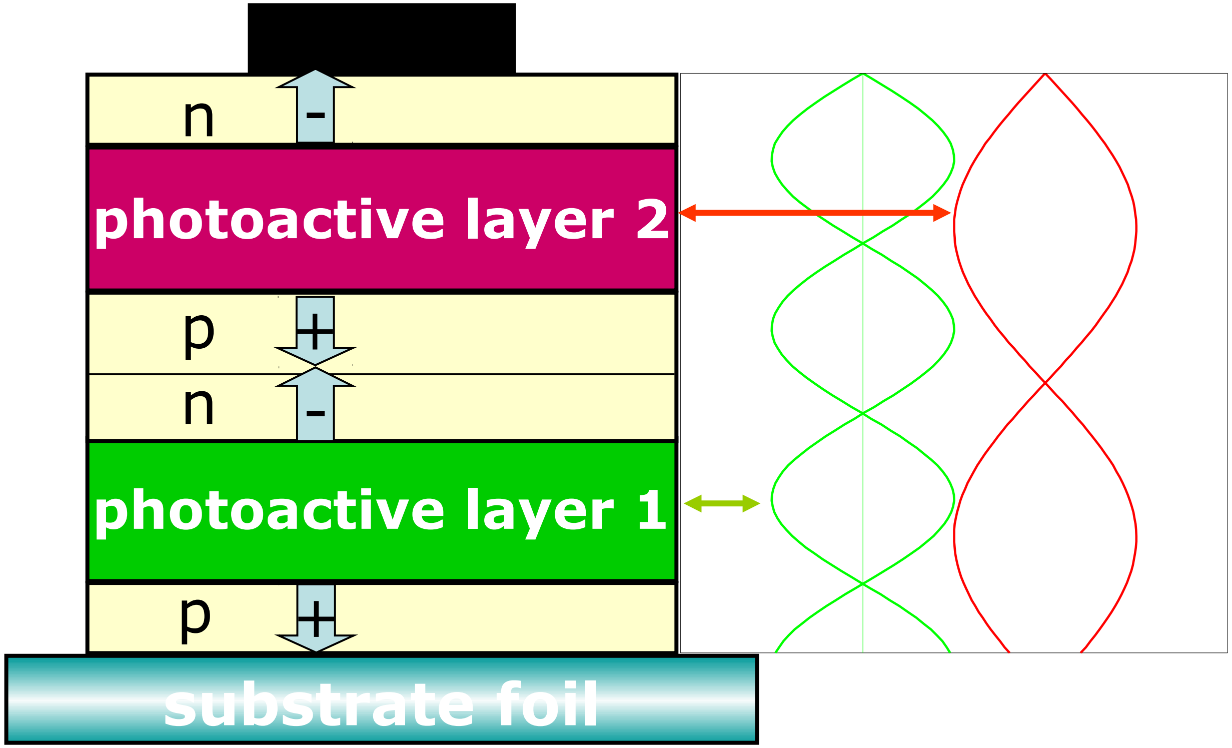
Main assumptions:

- EQE 60%
- FF 60%

	first cell	second cell	
e.gap	1.9eV	1.25eV	~21%
o.gap	*~770nm*	*~1300nm*	
e.gap	2.1eV	1.5eV	~20%
o.gap	*~690nm*	*~1030nm*	
e.gap	2.225eV	1.7eV	~19%
o.gap	*~645nm*	*~890nm*	

T. Mueller et al.

Pin-tandem cells:
doped layers are critical for optical optimization



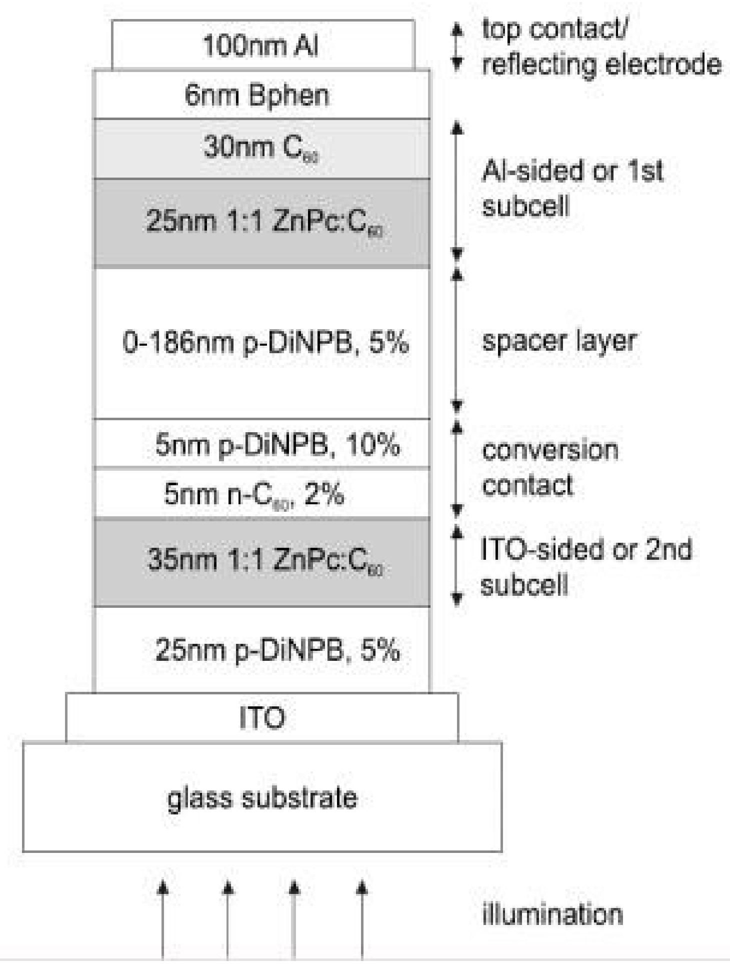
J. Drechsel et al., Appl.Phys.Lett. **86**, 244102 (2005)

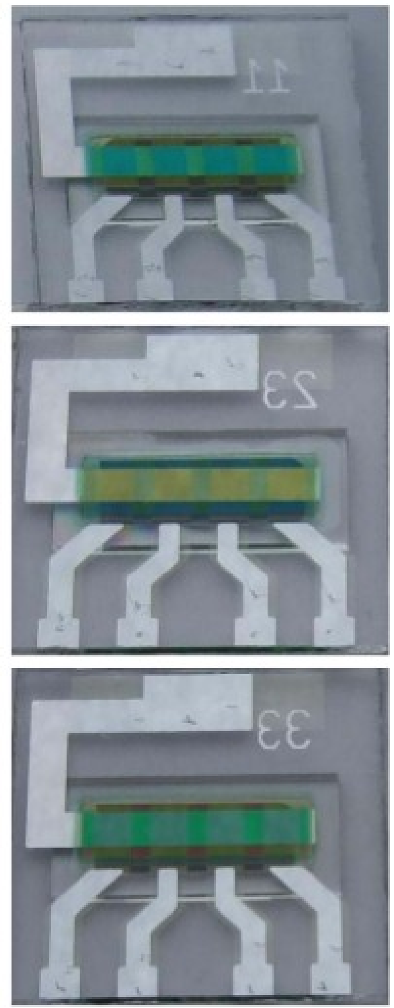
P-i-n tandem cells:

- Pn-junction is ideal recombination contact
- optimizing interference pattern with conductive transparent layers

=>optical engineering on nanometer layer thickness scale

Pin-tandem cells: placing absorbers in different field maxima





Thickness of spacer layer:

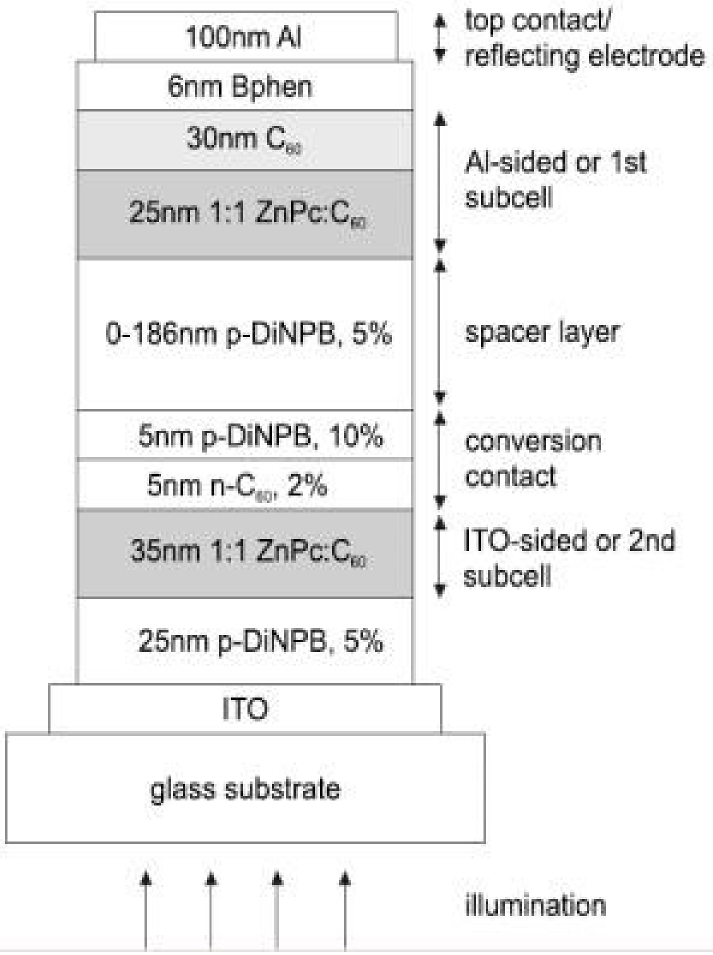
0 nm (1st max)

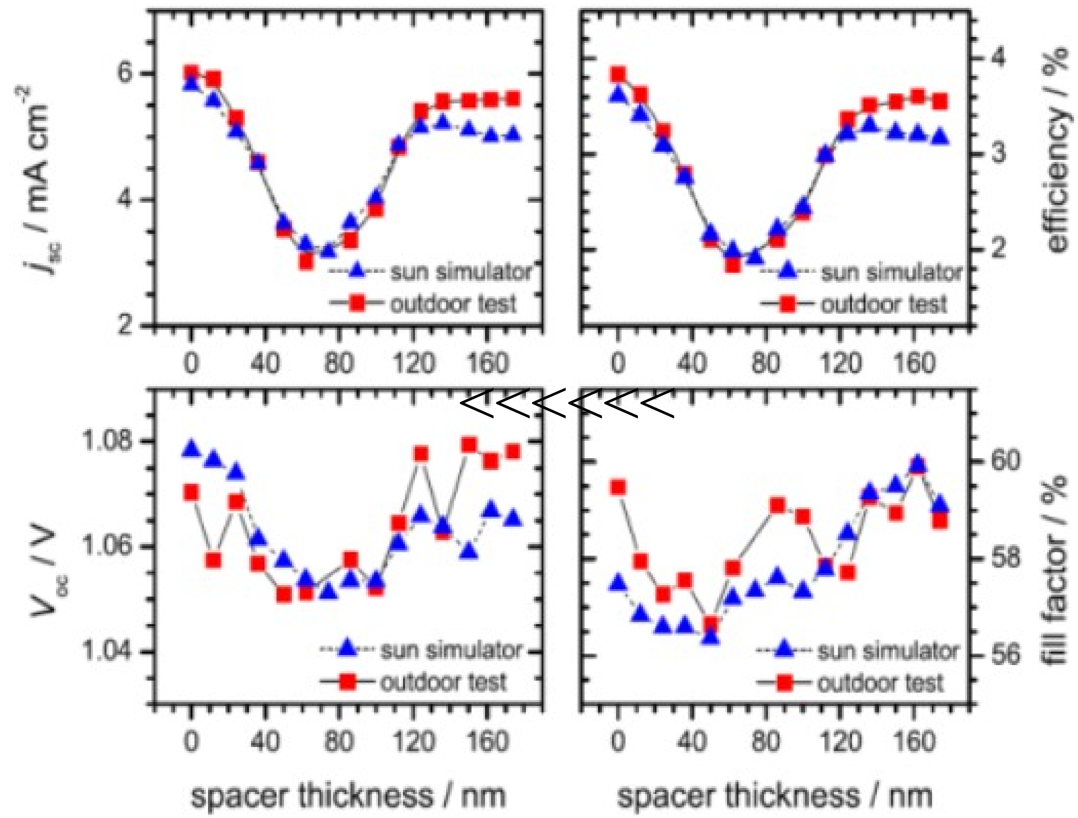
74nm (1st min)

124nm (2nd max)

R. Schüppel et al., J. Appl. Phys. **107**, 044503 (2010)

Pin-tandem cells: placing absorbers in different field maxima

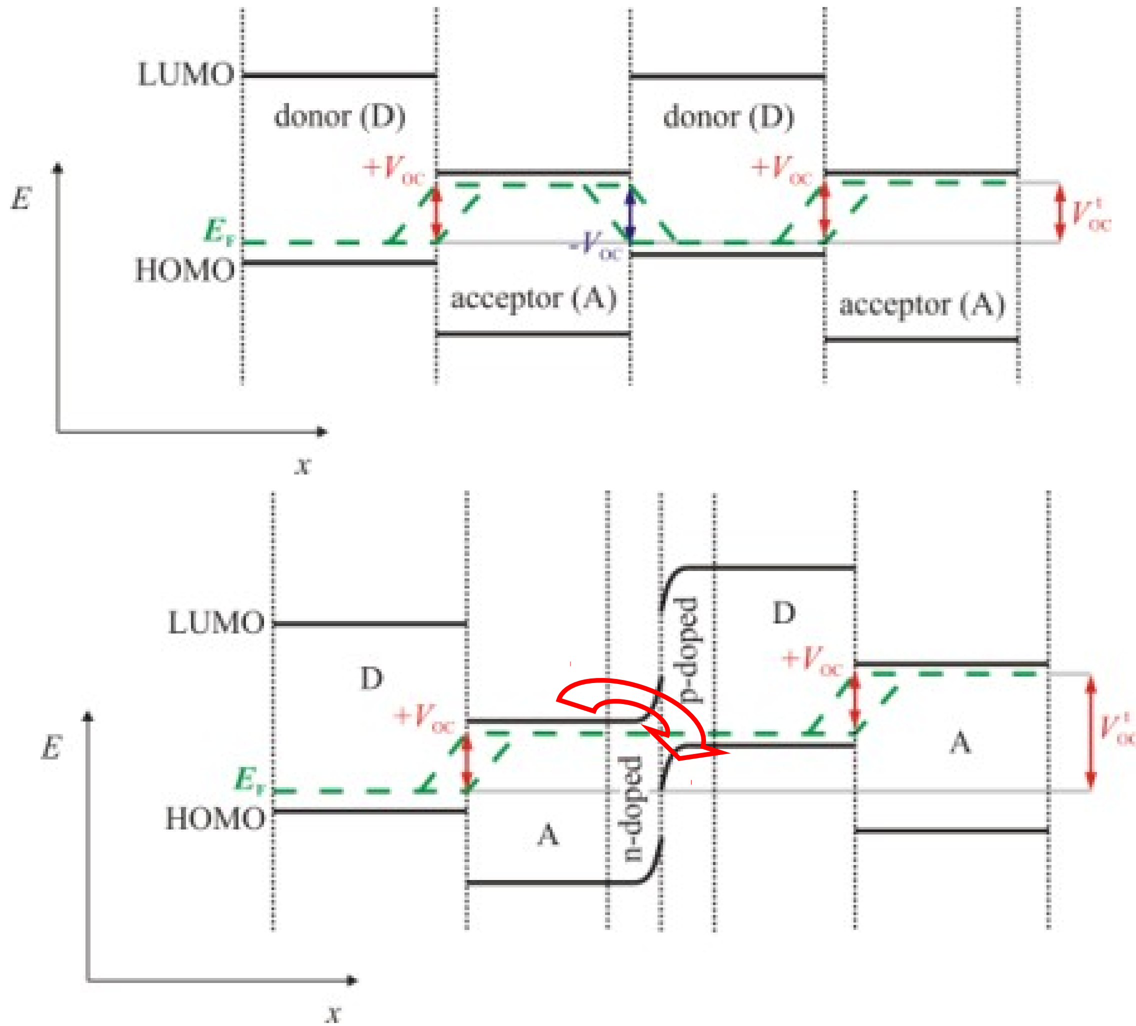




R. Schüppel et al., J. Appl. Phys. **107**, 044503 (2010)

Efficient Recombination Contact

- Stacking two D/A heterojunctions
  → reverse HJ
  → voltage loss

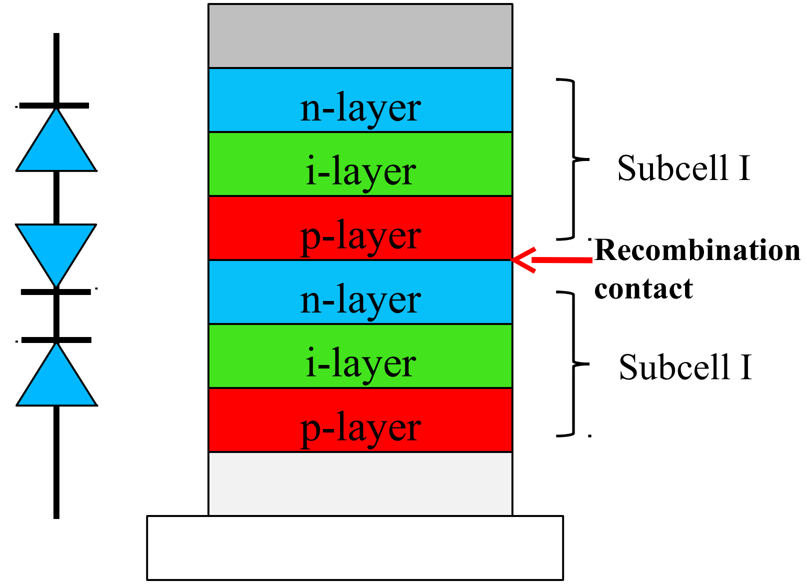


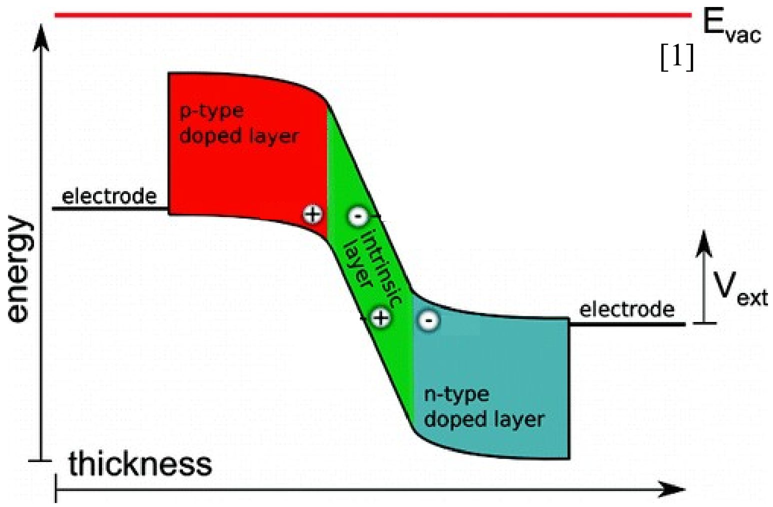
- Our Approach:
  - highly doped layers for energy level alignment at the interface
  - no quasi-Fermi level splitting
  - no loss of V_{oc}

R. Timmreck *et al.*, J. Appl. Phys. 108, 033108 (2010)

The physics of recombination contacts

- Organic pin-diodes used to study the recombination contact
- Systematic study on the reverse behavior depending on:
  - i-layer thickness
  - dopant concentration

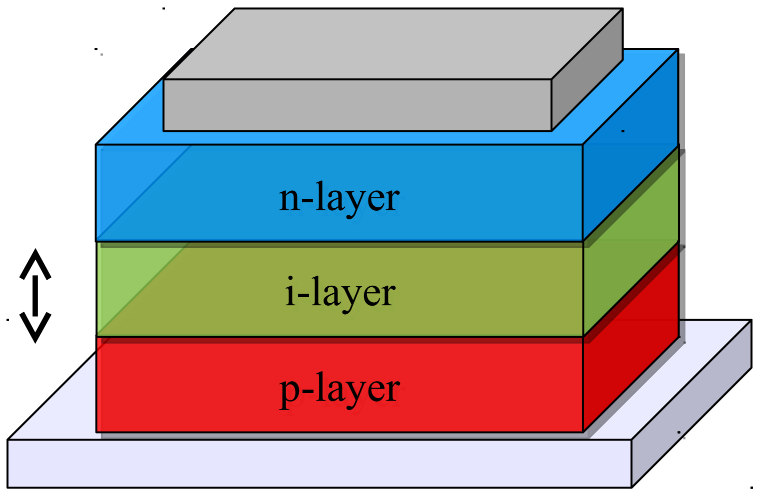


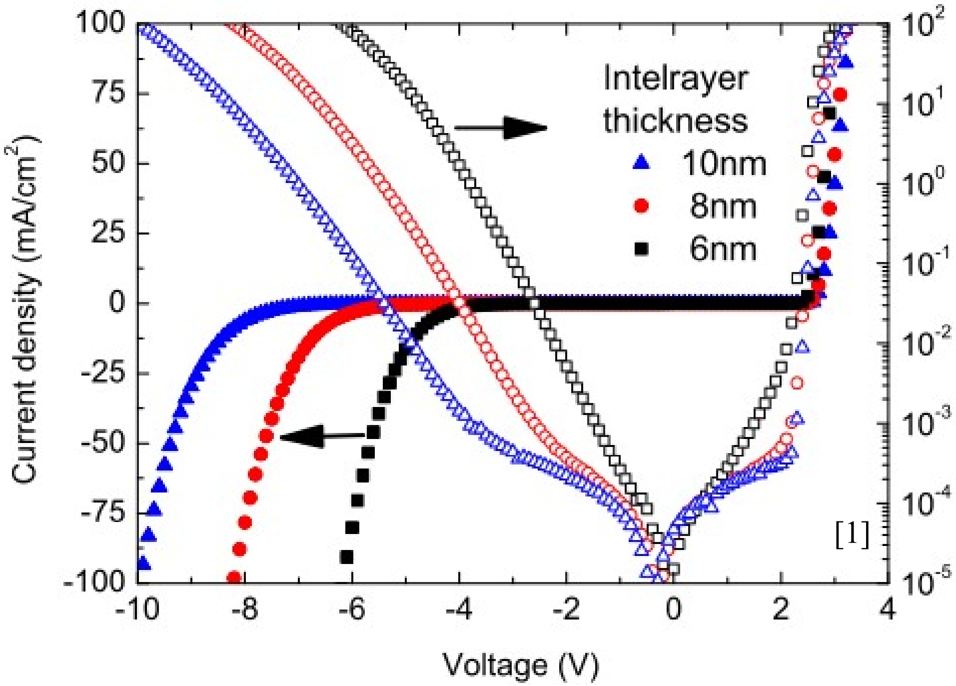


[1] H.Kleemann et al., Nanoletters 10, 4929, 2010.
[2] H.Kleemann et al., Org. Electron. 14, 193, 2013.
[3] H.Kleemann et al., J. Appl. Phys. 111, 123722, 2012.

The physics of recombination contacts: Zener tunneling

- Organic Homo-diode (Ir(piq)$_3$) [1,3]
- i-layer thickness from 1....12nm
- Reversible reverse breakdown obtained
- Breakdown controllable by i-layer thickness
- no effect on forward IV curve





[1] H.Kleemann et al., Nanoletters 10, 4929, 2010.
[3] H.Kleemann et al., J. Appl. Phys. 111, 123722, 2012.

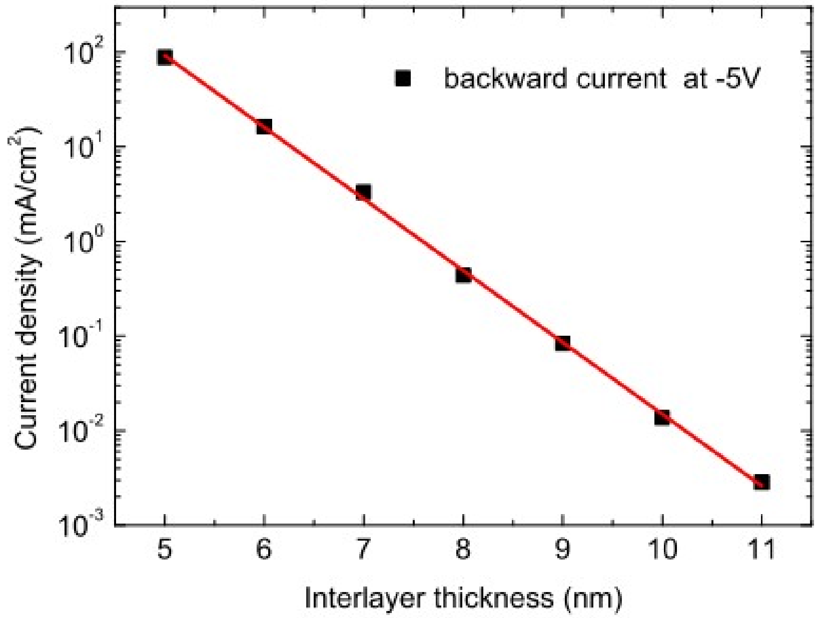
The physics of recombination contacts

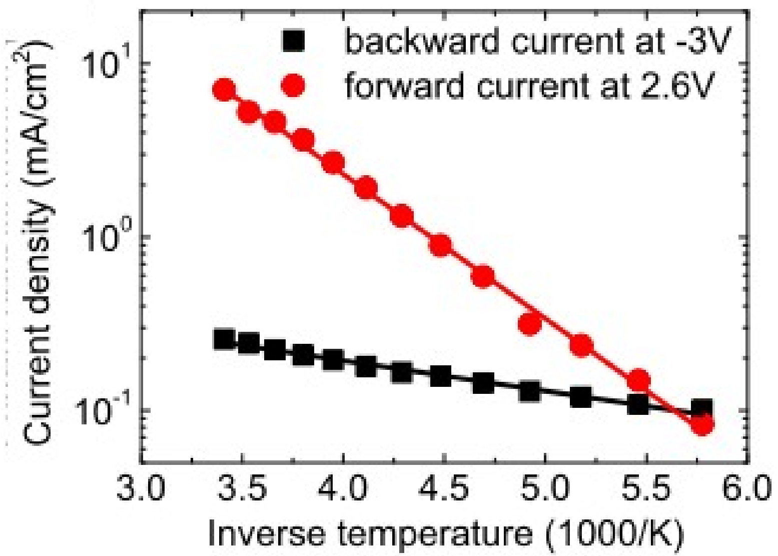
- Strong exponential thickness vs. current relation

- Reverse current also controllable by doping in the p- and n-layer

- Thermal activation of current
  - 30meV in reverse
  - 170meV in forward

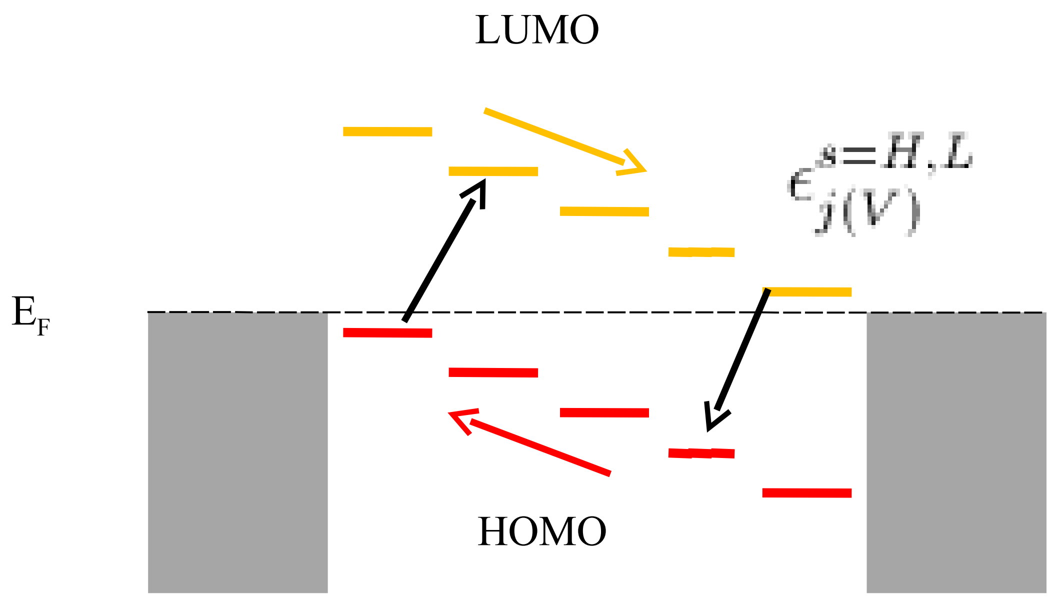
- Field and temperature dependence prove tunneling process





[1] H.Kleemann et al., Nanoletters 10, 4929, 2010.
[3] H.Kleemann et al., J. Appl. Phys. 111, 123722, 2012.

Theoretical description of recombination contacts

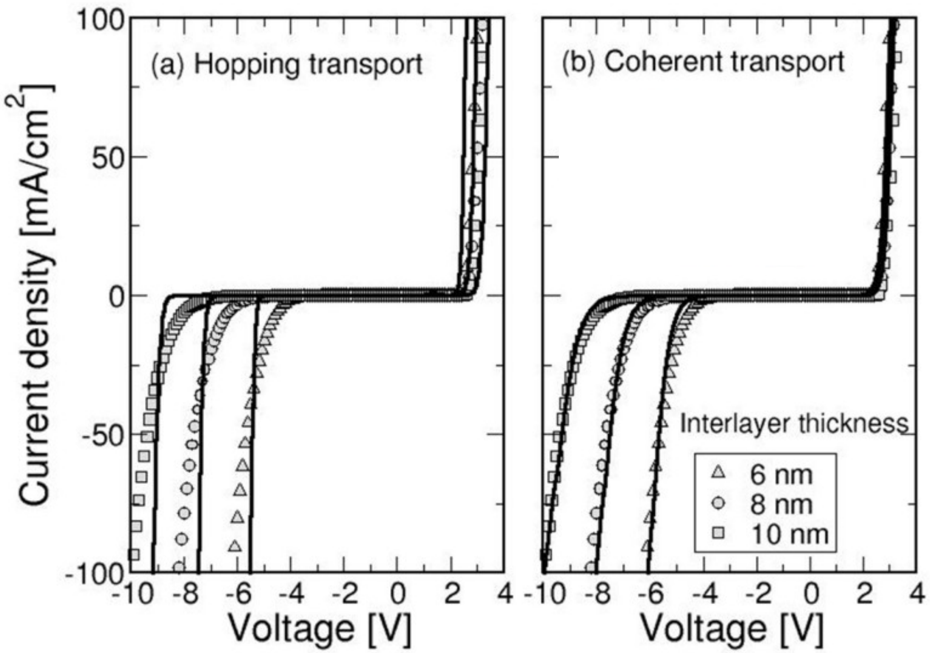


- Modeling of the i-layer by a linear electronic ladder with N blocks and two energy levels for each block

- Slope of the ladder deduced from the built-in potential determined by impedance analysis

[1] H.Kleemann et al., Nanoletters 10, 4929, 2010.
[2] H.Kleemann et al., Org. Electron. 14, 193, 2013.

Theoretical description of recombination contacts

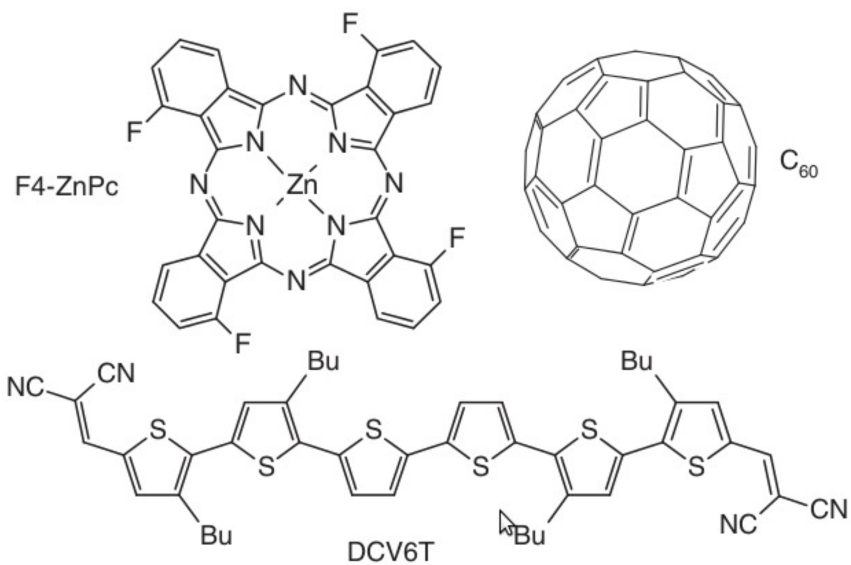


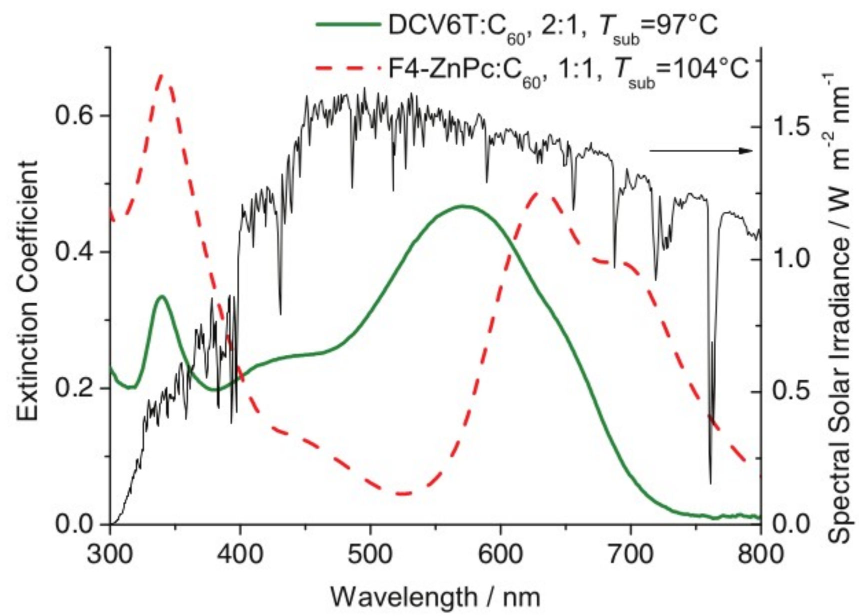
- Breakdown can be better described using coherent transport (incoherent transport might be dominant on larger scales)

- Tunneling between HOMO and LUMO of nearest neighbors if levels are nearly aligned

DCV6T:F4-ZnPc tandem cells

- Combination of thiophene and phthalocyanine
- Absorption bands only reasonably separated

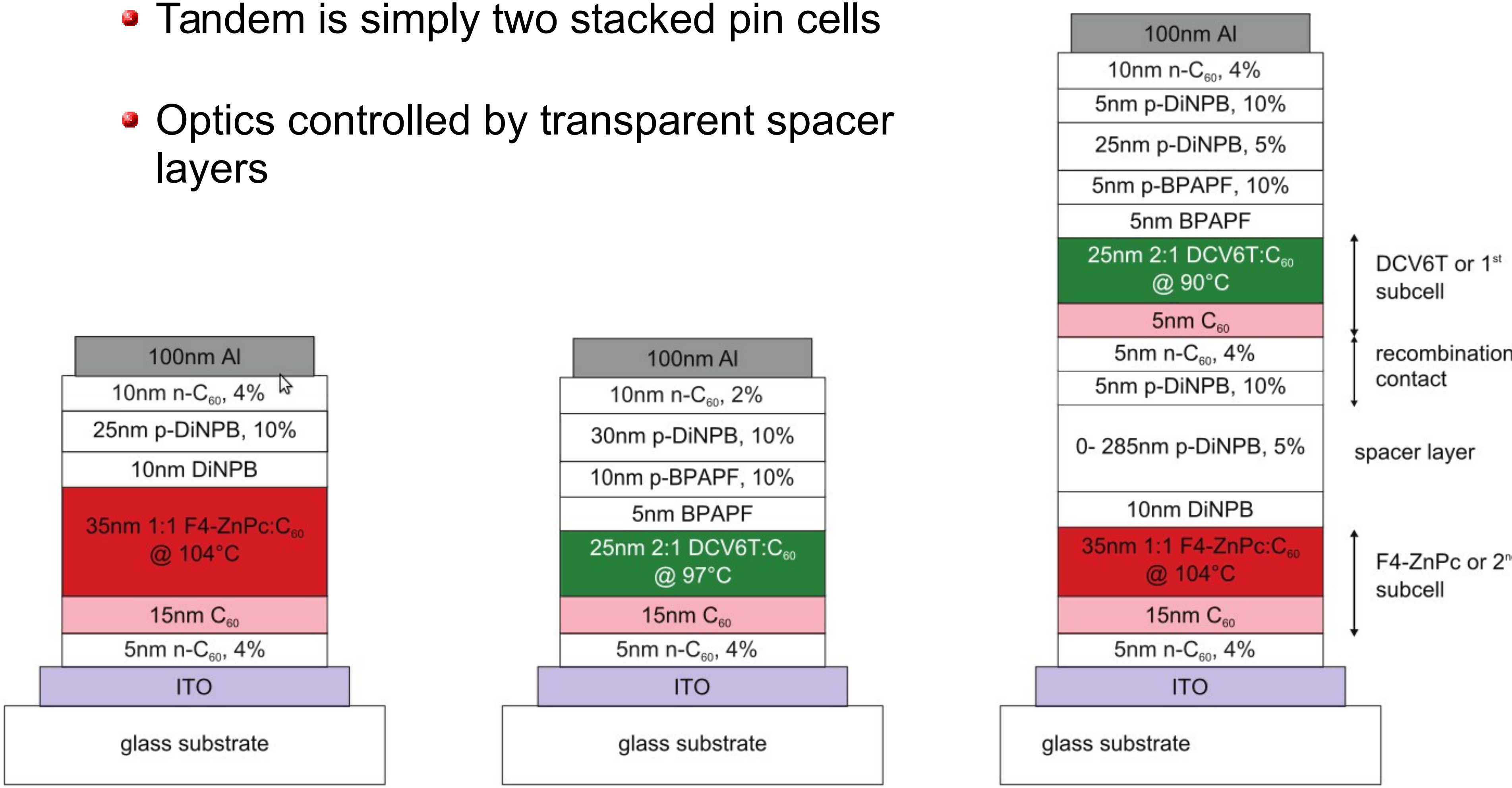




M. Riede et al., Adv. Funct. Mat. **21**, 3019 (2011)

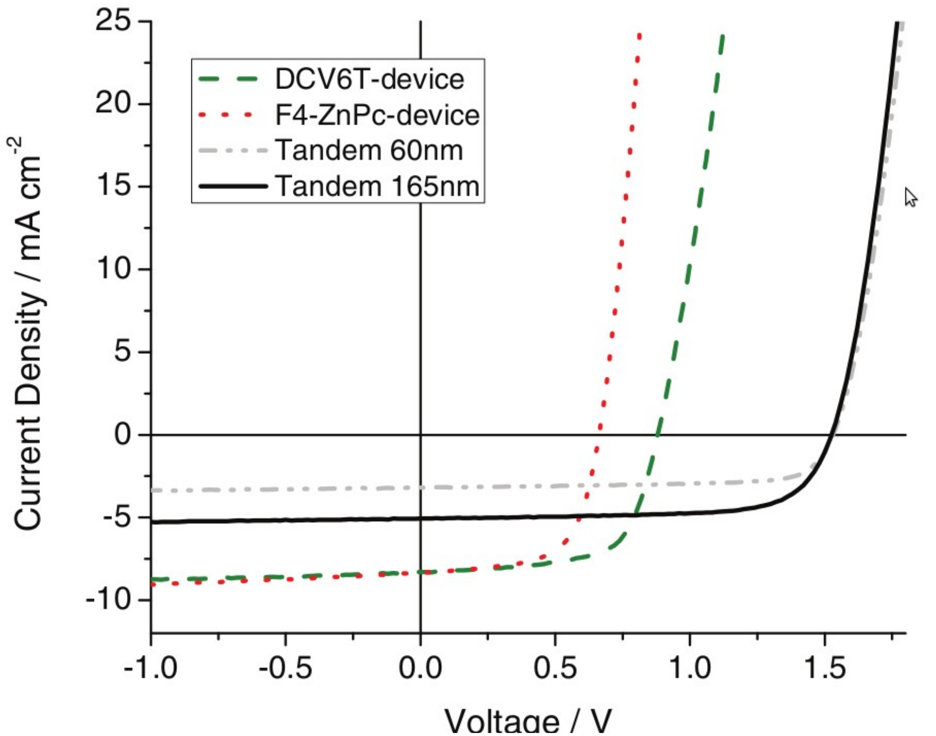
DCV6T:F4-ZnPc tandem cells

- Tandem is simply two stacked pin cells
- Optics controlled by transparent spacer layers



DCV6T:F4-ZnPc tandem cells

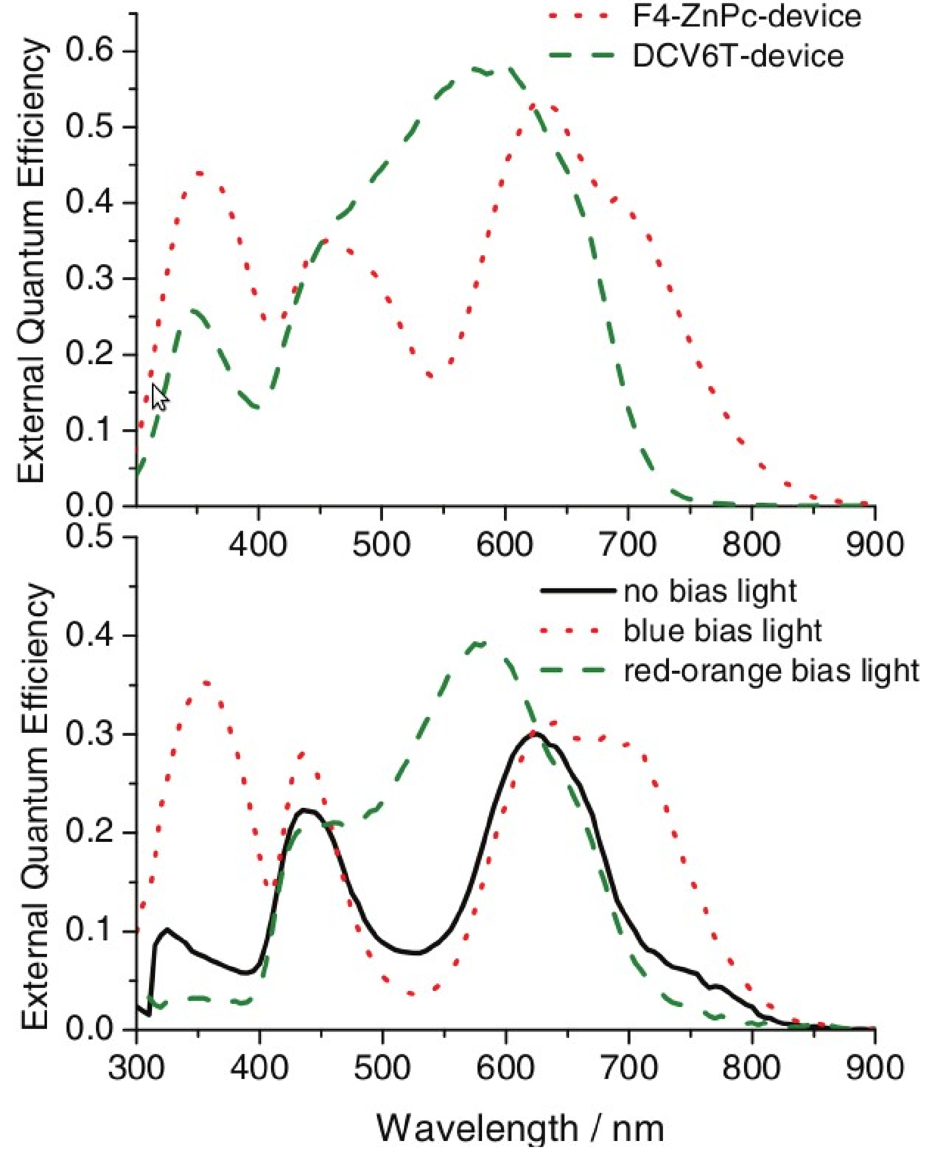
- Voltage almost perfectly doubled
- Significant loss in current
- Fill factor for tandem higher: 74%



	V_{oc} [V]	j_{sc} [mA cm^{-2}]	FF [%]	mismatch	Intensity [mW cm^{-2}]	η %
F4-ZnPc-device	0.66	8.3	64	0.99	100	3.9
DCV6T-device	0.88	8.3	66	1.08	111	4.3
Tandem 60nm	1.53	3.2	74	–	98*	3.6*
Tandem 165nm	1.52	5.0	71	–	98*	5.6*

EQE of DCV6T:F4-ZnPc tandem cells

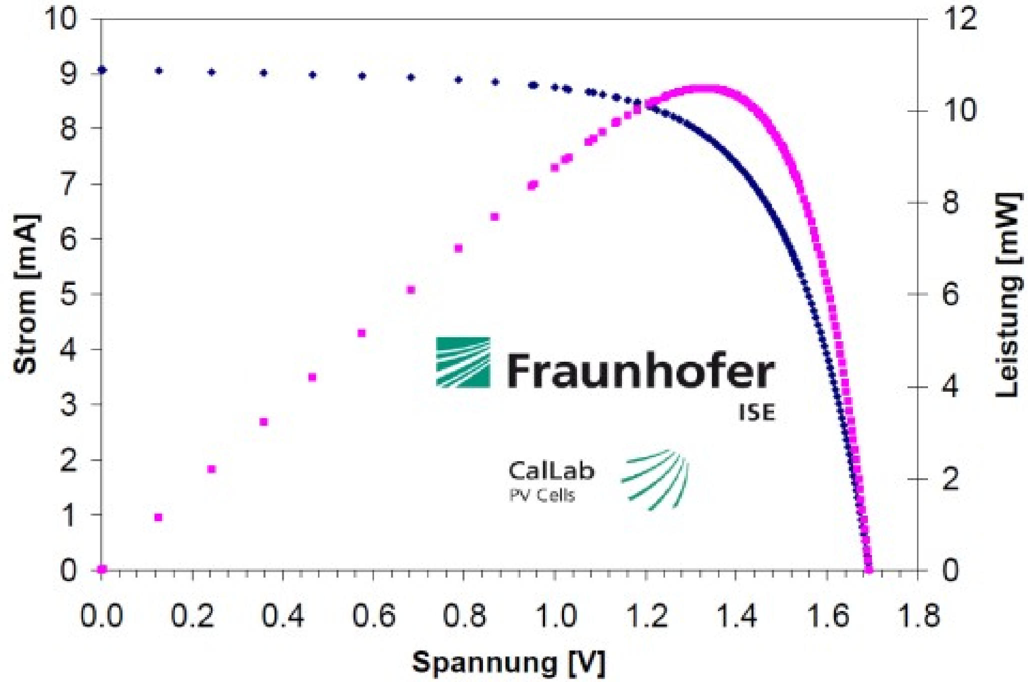
- Tandem system has significant overlap of absorption
- EQE spectra are nevertheless well separated
- EQE low due to thin absorber layers



Small-Molecule OPV Record > 1cm²

Leerlaufspannung:	V_{OC}	=	(	1.6930	±	0.0085	) V
Kurzschlussstrom:	I_{SC}	=	(	9.08	±	0.23	) mA
Füllfaktor:	*FF*	=	(	68.27	±	0.68	) %
Wirkungsgrad:	η	=	(	9.75	±	0.30	) %

9.7 % on 1.1cm² certified by Fraunhofer ISE, Germany



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Say hello to solar. Wherever you are

Small-Molecule OPV Record > 1cm²

12 % Efficiency – new world Record for OPV

Measured by SGS at standard test conditions (December 2012)

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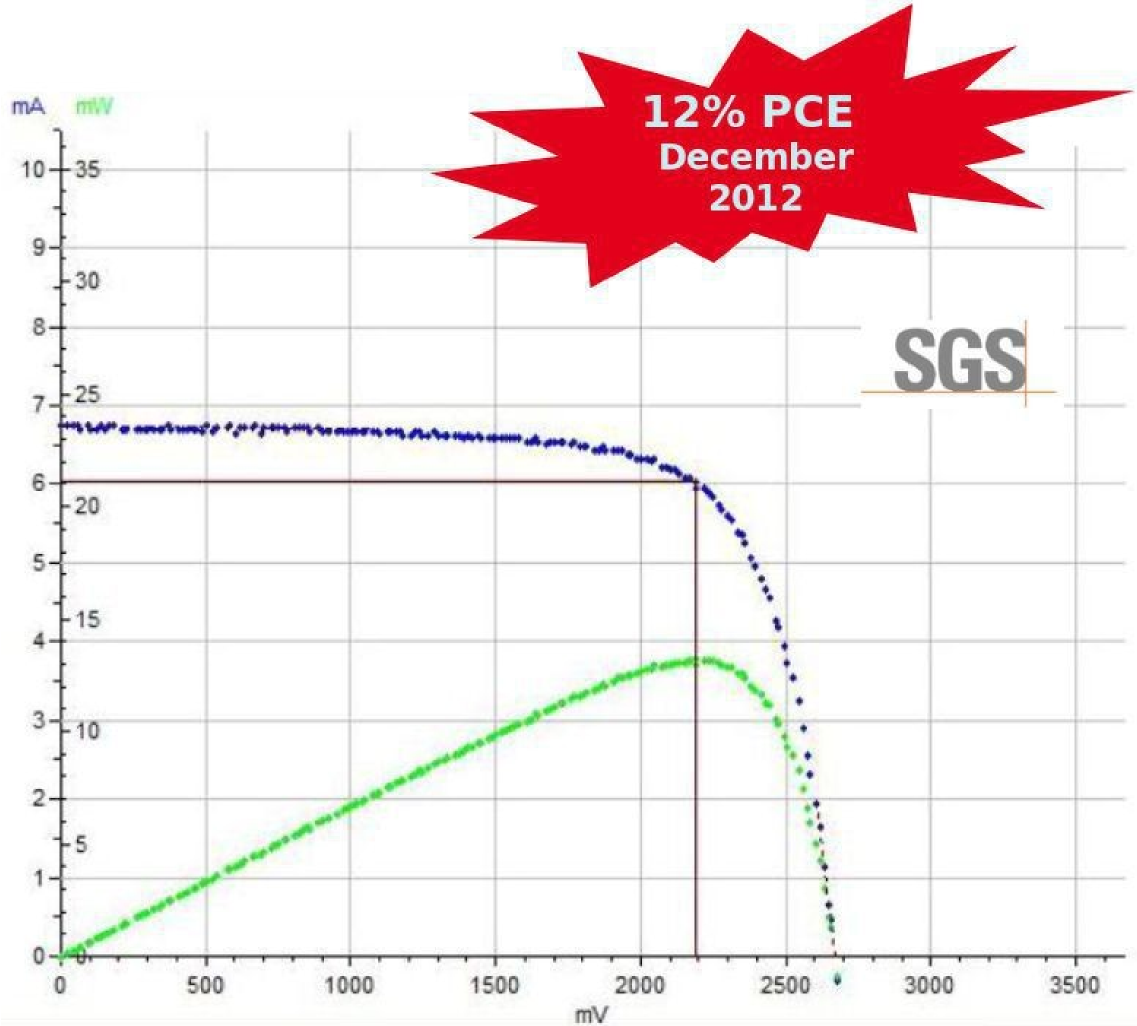

Module ID code :	see SNR
Serial number :	31004_120760899
Mon. cell type =	HeliatekKG2
Id. number =	kal.: VLSI 10510-008
Sensitivity =	110.44 mV/(kW/m²)
Mode name =	Heliatek
Method name =	Direct
Sample number =	222
Sample time =	40 us
Measurement duration =	8.880 ms
N° measure =	1
Irrad =	1.000 kW/m²
Temp =	25.0 °C
Avg.Ir. =	1.001 kW/m²
Dev.Ir. =	0.001 kW/m²
Isc =	6.730 mA
Voc =	2674.07 mV
EffC =	12.0 %
EffM =	12.0 %
FF =	73.5 %
MPP =	13.23 mW
V@mpp =	2187.69 mV
I@mpp =	6.049 mA
Rser =	35.700 Ohm
Rsht =	34215.76 Ohm

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OPV Module record

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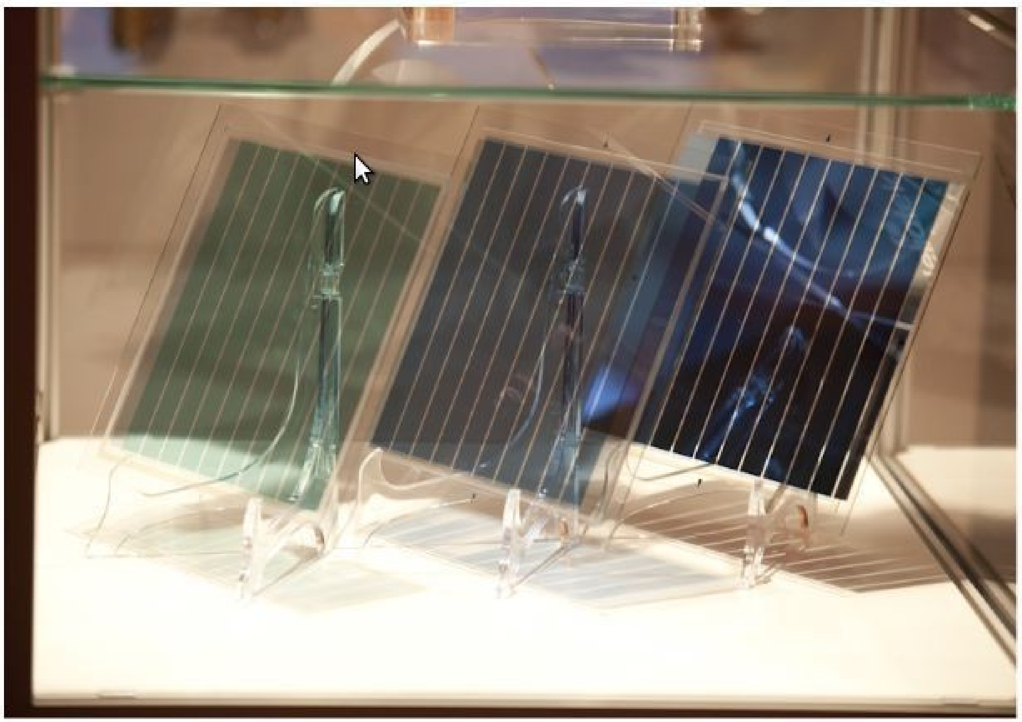
9% Module Efficiency on Glass

Record efficiencies thanks to minimum upscaling losses



7 Cells in Series	**Active Area 122 cm²**	**Total Area 142 cm²**
VOC	11.8 V	11.8 V
VOC per cell	1.67 V	1.67 V
JSC mA/cm²	1.21	1.04
FF	63 %	63 %
Efficiency	**9.0 %**	**7.7 %**

Latest news: 9.8% on active area of 122 cm² module

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Development of OPV Efficiencies

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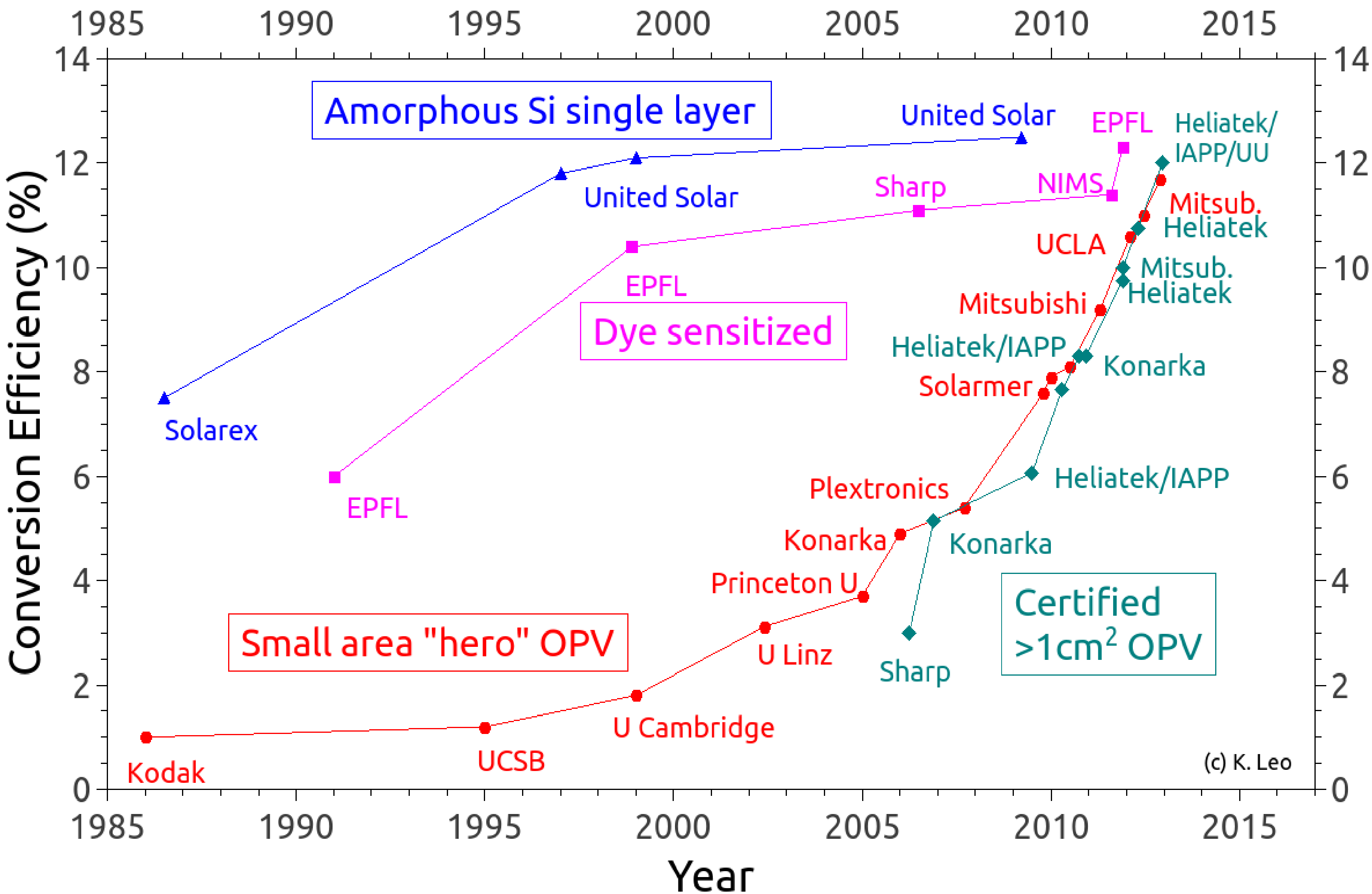

diagram available under www.orgworld.de

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Organics is more: The O-Factor

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- Standard measurement: 1 sun, 25 ^{0}C, perpendicular incidence

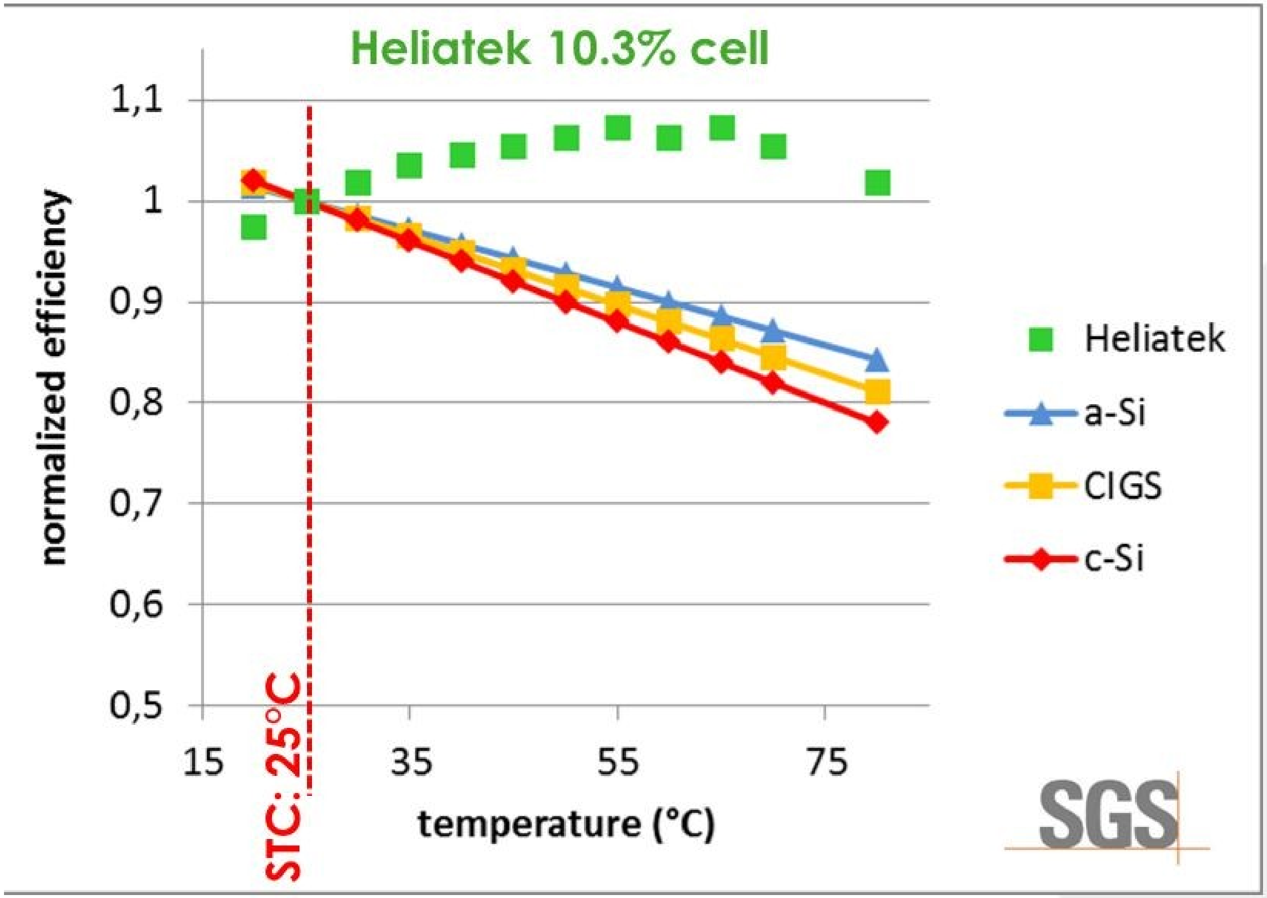
- Reality: 40-60 ^{0}C, often less than 1 sun, diffuse light

- Organics:
  - Positive temperature coefficient
  - Higher efficiency for lower intensity
  - Special diffuse light responsivity

- Sums up in the O-Factor: up to 30% better harvesting!

Temperature performance

Positive temperature coefficient

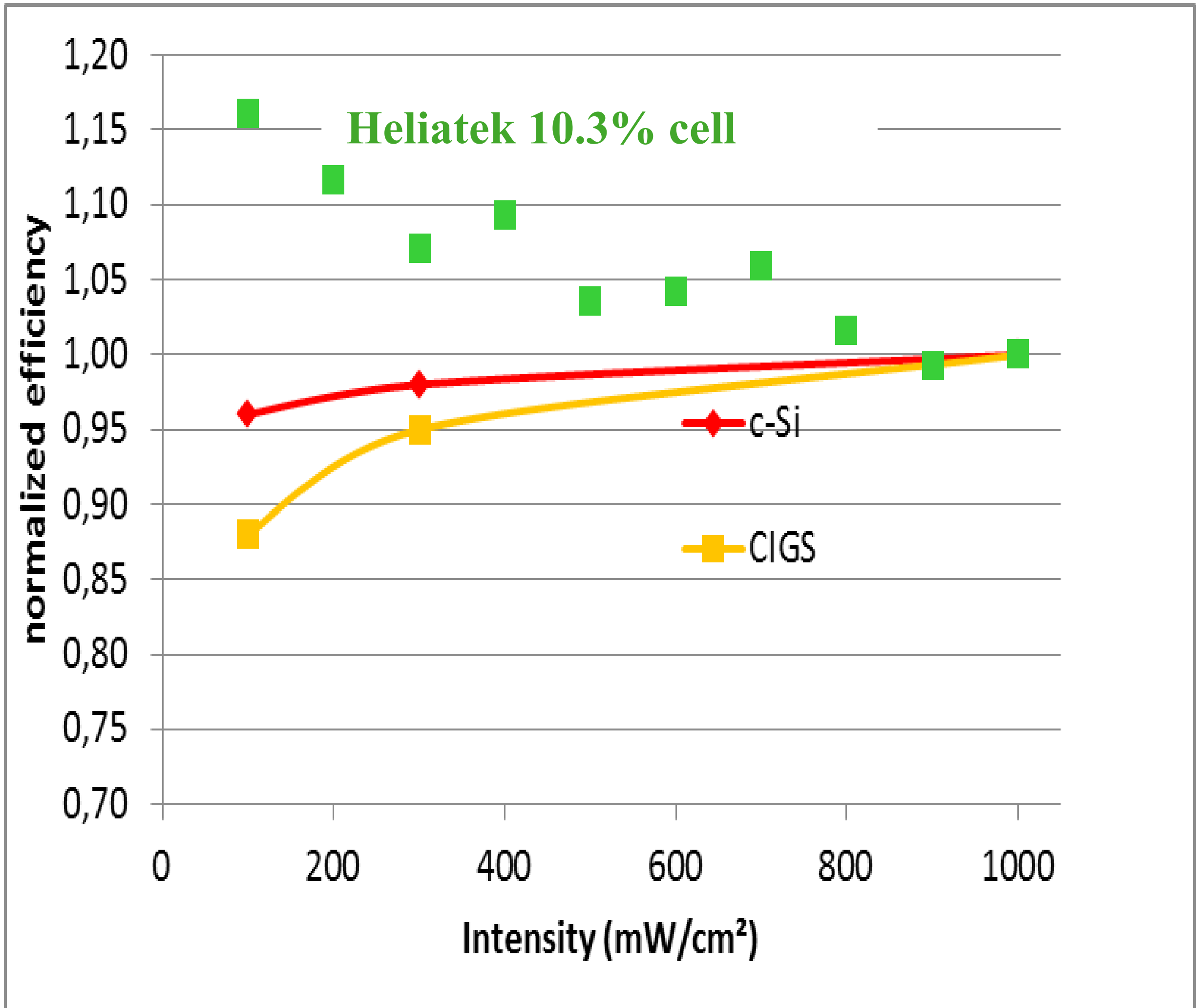


- **Heliatek OPV: Efficiency has broad maximum between 30°C and 60°C**
- c-Si and CIGS:

  15 % lower efficiency at 60 °C
- µc-Si/a-Si:

  10 % lower efficiency at 60 °C

Top Real Life Performance: Superior low-light performance



Heliatek:

>110 % of full-sun

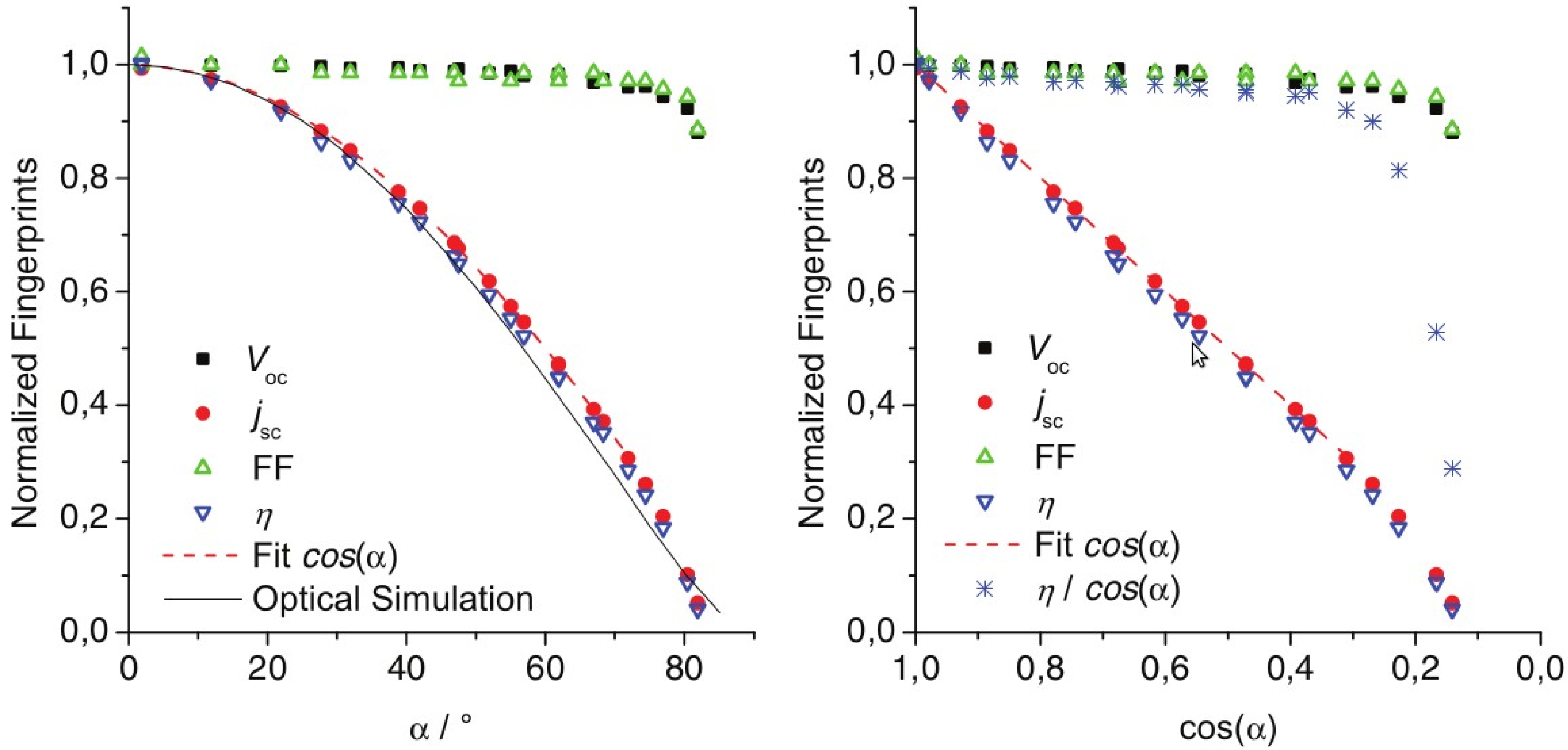
efficiency at 1/10th sun

Measurement by
SGS Fresenius

April 2012

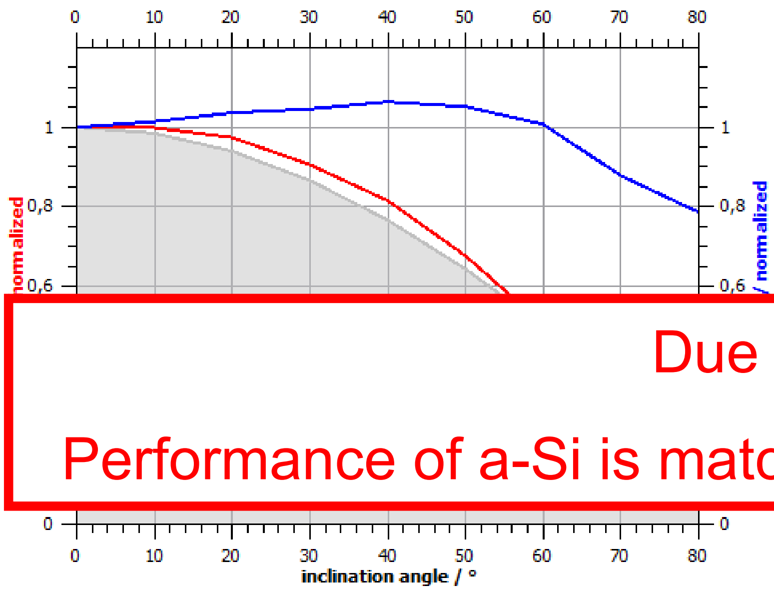
Angular Dependence for Tandem Cells

- DCV6T:F4-ZnPc tandem cell
- Cells follow Lambertian behavior
- Result follow optical simulation



M. Riede et al., Adv. Funct. Mat. **21**, 3019 (2011)

Incident Angle Performance



Due to O-Factor:

Performance of a-Si is matched already with 8.3% technology!

High independence on incident angle:

Efficiency development from 0 to 60° above the expected values of pure geometrical consideration

- Heliatek Absorber
- Certified Efficiency: **8.3 %** (1 cm²)
- Collaboration of Heliatek und IAPP (TU Dresden)

Outline

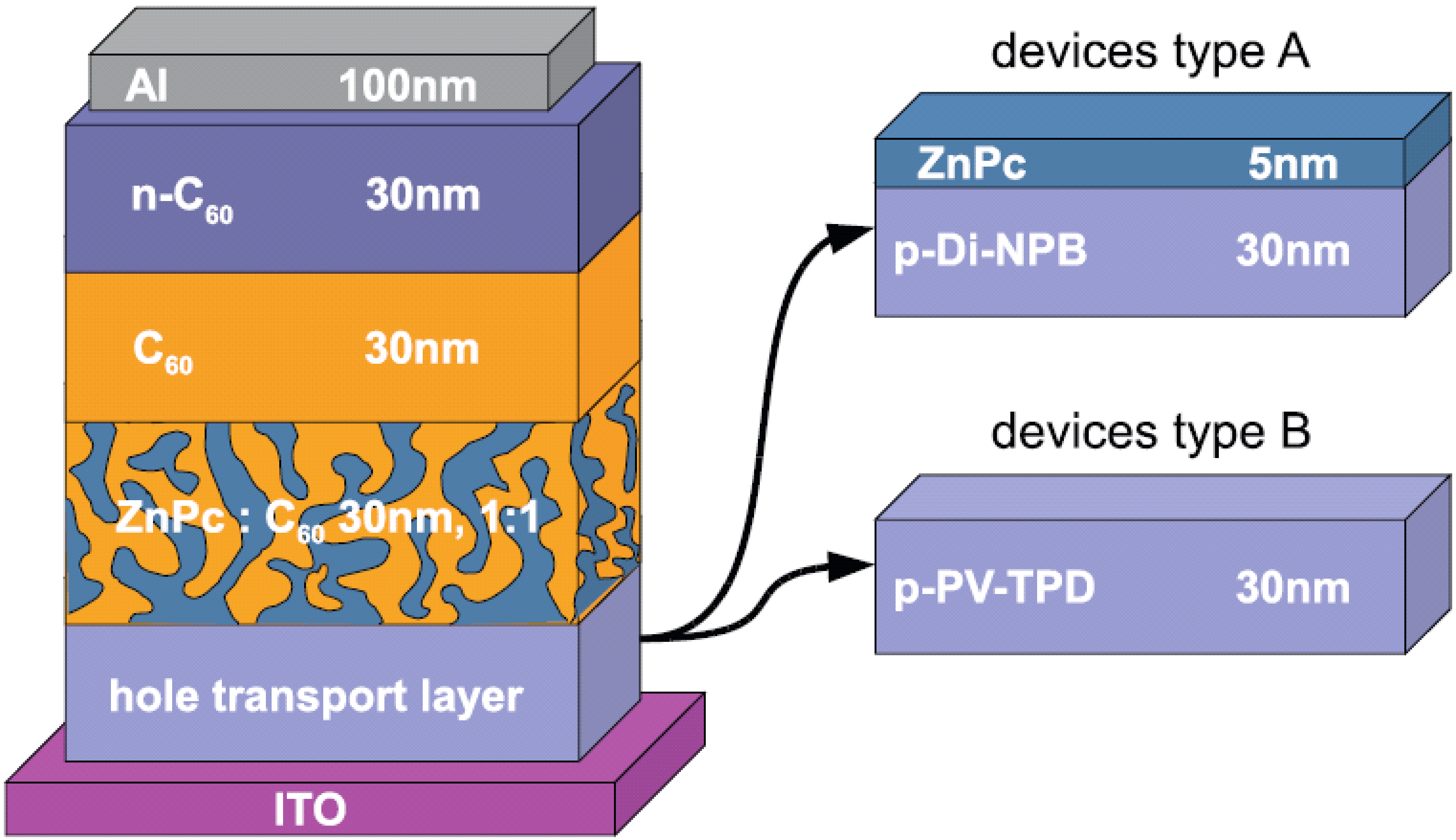
- Motivation
- Basics of organic solar cells
- Materials requirements for organic solar cells
- Exploring the thiophene zoo
- Tandem organic cells
- **<u>Lifetime&Manufacturing</u>**

Lifetime measurements

- Water and oxygen induced degradation of small molecule organic solar cells, M. Hermenau, M. Riede, K. Leo, S. Gevorgyan, F. Krebs, and K. Norrman, Solar Energy Materials & Solar Cells **95**, 1268-1277 (2011)

- Total charge amount as indicator for the degradation of small molecule organic solar cells, M. Hermenau, S. Scholz, K. Leo, and M. Riede, Solar Energy Materials & Solar Cells **95**, 1278-1283 (2011)

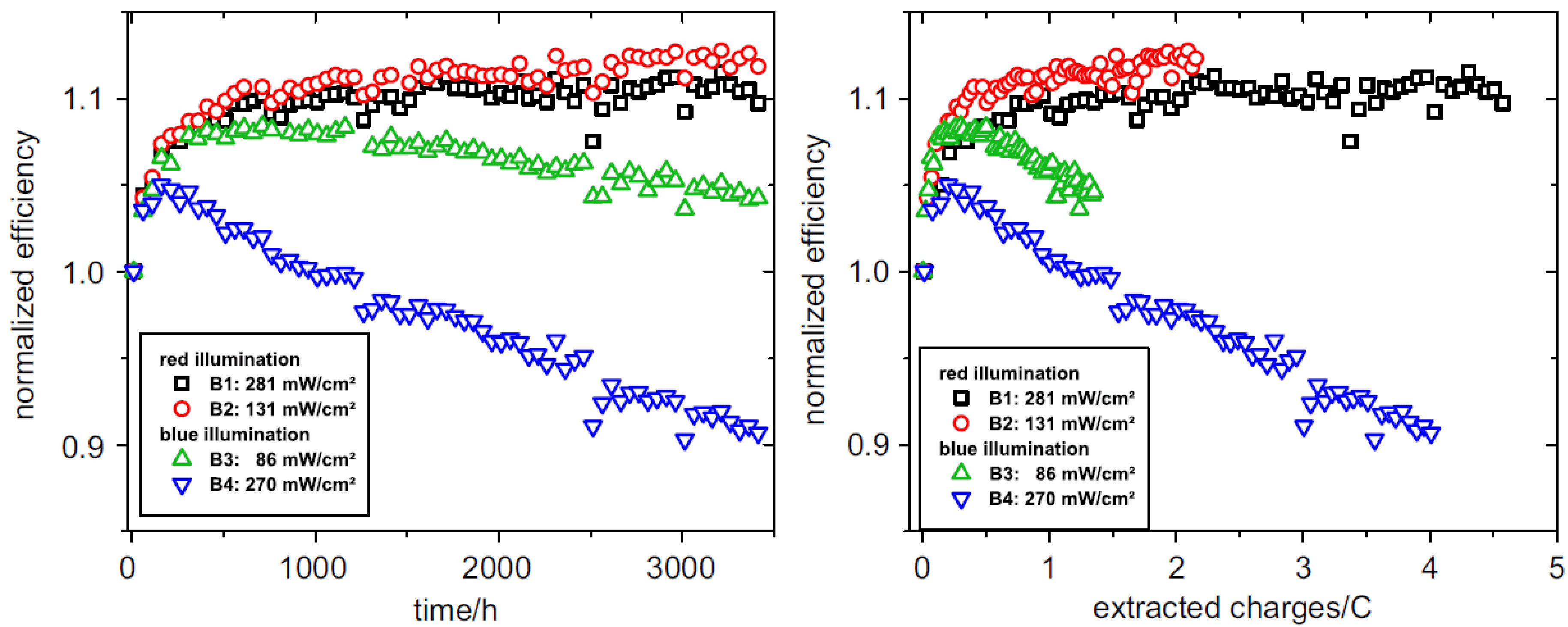
Dependence of aging on photocurrent



M. Hermenau et al., Solar EnergyMaterials&SolarCells **95,** 1278 (2011)

Dependence of degradation on photocurrent

- Degradation is directly proportional to photocurrent



M. Hermenau et al., Solar EnergyMaterials&SolarCells **95,** 1278 (2011)

Influence of water and oxygen

- ZnPc/C60 bulk heterojunction as model system
- Isotope techniques used to study oxygen and water diffusion
- Comparison of wet oxygen, dry oxygen, and dry nitrogen
- Analysis with TOF-SIMS and XPS

M. Hermenau et al. Solar En. Mat. & Solar Cells **95**, 1268 (2011)

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Results of degradation study

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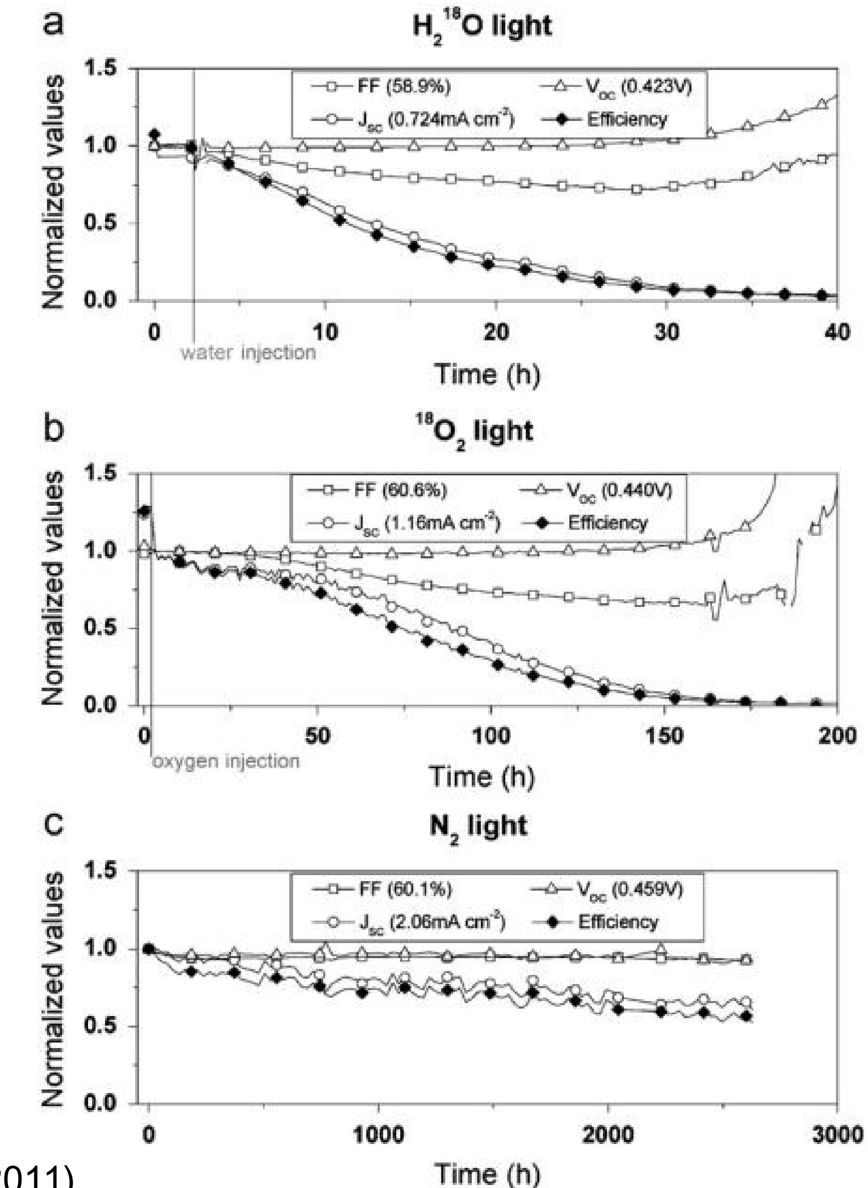
- Mainly current and FF degrade; V_{oc} is rather stable

- Water is much more relevant than oxygen

  - Water leads to oxidation of Al electrode

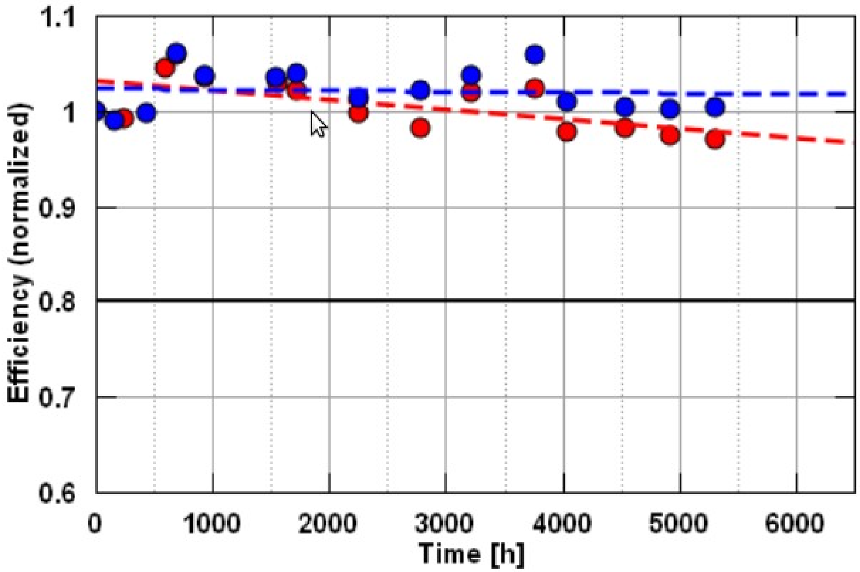
  - Water induced ZnPc degradation



M. Hermenau et al. Solar En. Mat. & Solar Cells **95**, 1268 (2011)

Lifetime of Thiophene Tandem Cells

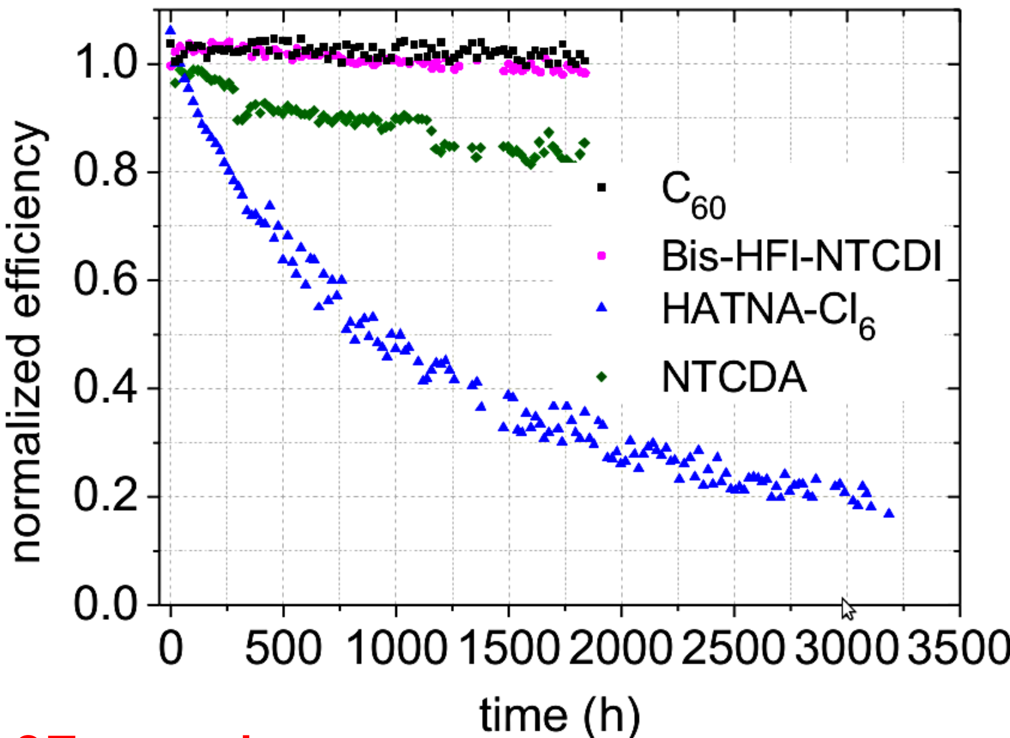
- State-of-the art Tandem device
- Collaboration between Heliatek & IAPP
- Absorber materials from BASF and Heliatek, dopants from Novaled
- Glass-glass encapsulation
- Halogen light at about 1.5 suns



Stress Conditions	Device Temperature	Integrated Light Dosis	Corresponding Exposure Time in Middle Europe
● (blue)	50°C	8.1 MWh/m²	8 y
● (red)	85°C	dark	

Lifetime of ZnPc:C_{60} lab cells

- Pin structures
- Glass-glass encapsulated
- Measured unter 2 suns

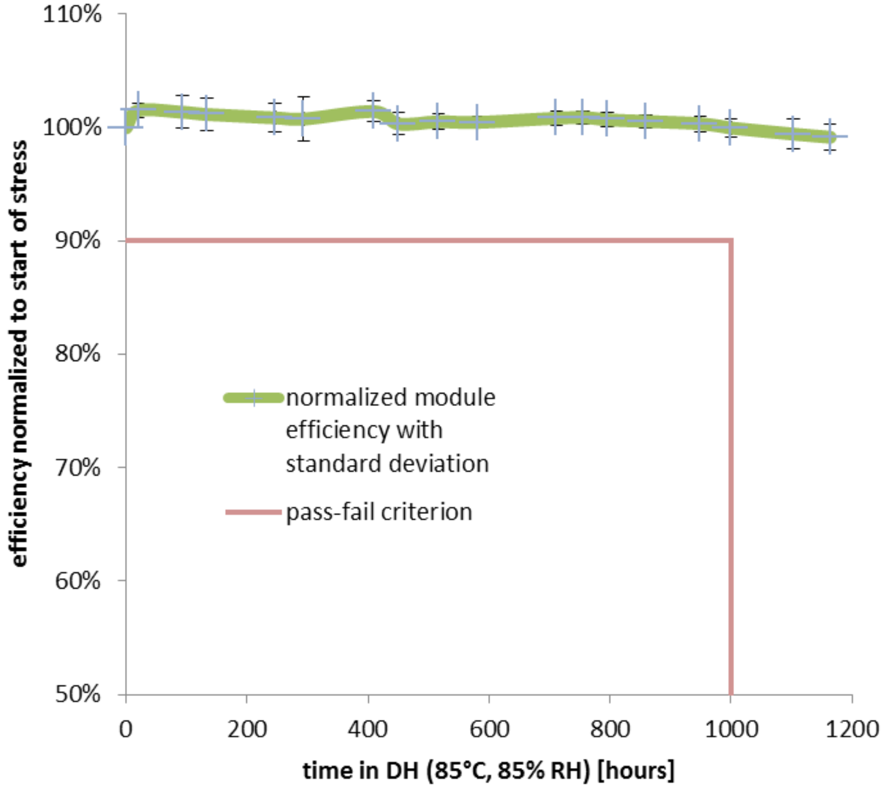


(Roughly) extrapolated lifetime: 37 years!

Christiane Falkenberg, PhD thesis, TU Dresden

Lifetime of flexible module

- IEC standard damp heat test



Heliatek reliability lab measurement of BDR-based stack, 80 cm² active area

- Heliatek's foil-encapsulated solar films withstand lifetime tests well above industry standard PV limits
- Graph shows degradation of power generation after damp-heat stress (85°C, 85% RH)
  below 3%
- Based on commercially available barrier foils
- Heliatek propriety encapsulation and sealing process

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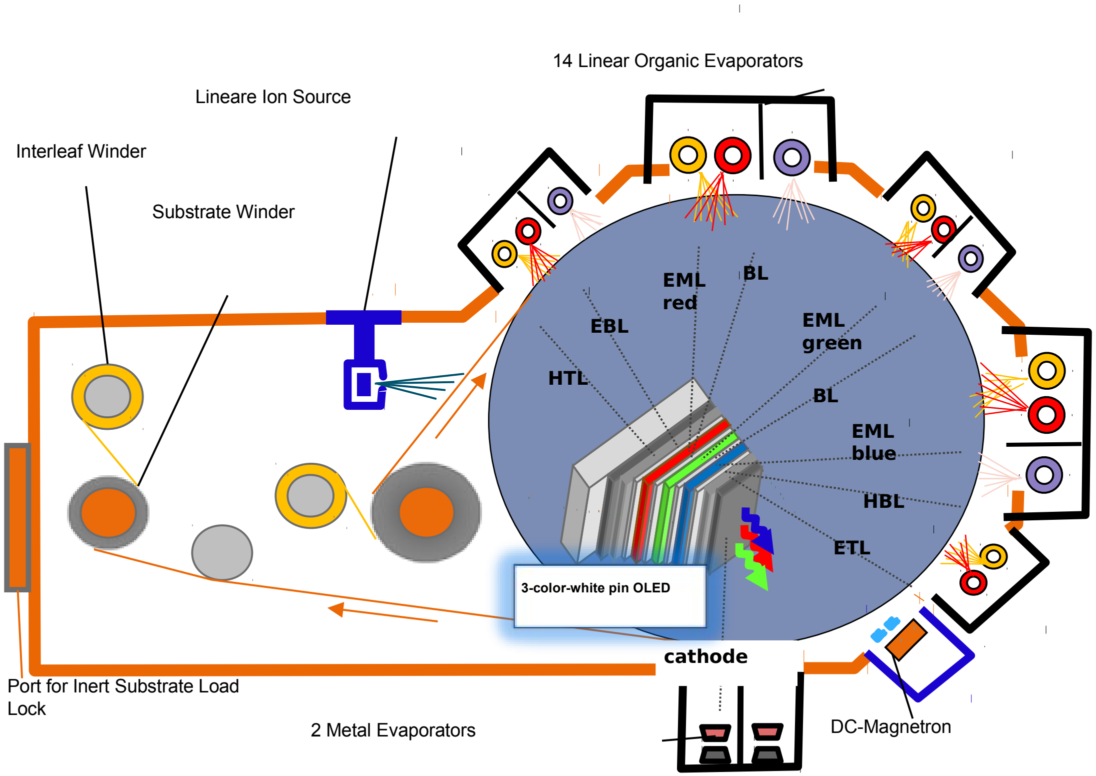
Heliatek Roll coater

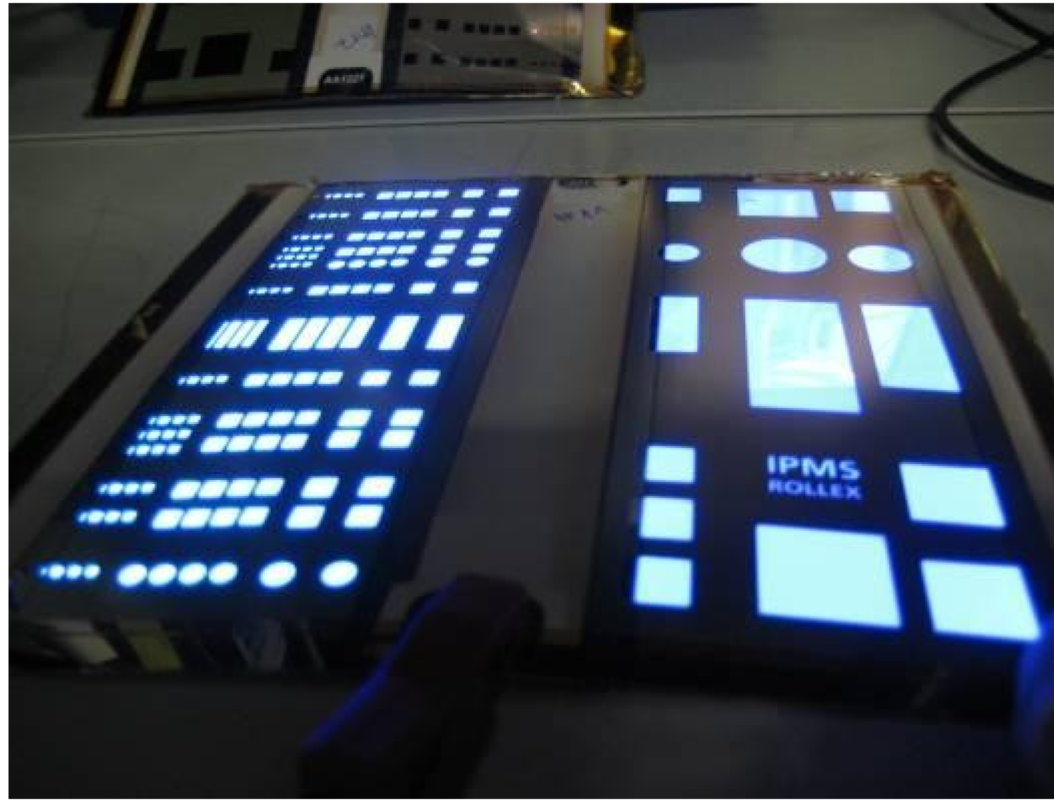
Roll-to-Roll Vacuum Coater



VON ARDENNE

Fraunhofer COMEDD

WHITE PIN OLED



top emitting OLED on metal sheets

Transparent OLED on Polymer web

Fraunhofer
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Conclusions

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- OPV has made major progress in the last few years
- Nanostructures and morphology control are key factors
- Tandem cells should allow lab efficiencies up to 20%
- Organic solar cells show superior harvesting properties
- Long lifetimes >20 years seem possible
- Low cost roll-to-roll processing demonstrated

Acknowledgment

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