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

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EASAC Workshop, Stockholm, 19.-20. September 2013
Acknowledgments

- Chris Elschner
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- Konrad Crämer
- Peter Bäuerle
- Roland Fitzner
- Egon Reinold
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
Potential of Organic Photovoltaics

- 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
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
Estimating the manufacturing cost of purely organic solar cells

Joseph Kalowekamo\textsuperscript{1}, Erin Baker\textsuperscript{*}

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\textsuperscript{2}. Under the assumption of 5% efficiency, this leads to a module cost of between $1.00 and $2.83/W\textsubscript{p}. Under the assumption of a 5-year lifetime, this leads to a levelized cost of electricity (LEC) of between 49\textcent and 85\textcent/kWh. In order to achieve a more competitive COE of about 7\textcent/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

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>OSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type used</td>
<td>Cost estimate ($/m²)</td>
</tr>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>C₆₀, CuPc &amp; SnPc</td>
</tr>
<tr>
<td>Electrical contacts and interconnects</td>
<td>Aluminum, silver paint</td>
</tr>
<tr>
<td>Substrate⁠</td>
<td>Flexible Plastic, ITO</td>
</tr>
<tr>
<td>Protective cover</td>
<td>Flexible encapsulant</td>
</tr>
<tr>
<td>Sealant</td>
<td>Surlyn</td>
</tr>
<tr>
<td>Packaging material</td>
<td>–</td>
</tr>
<tr>
<td>Specialty chemicals</td>
<td>4 TBP</td>
</tr>
<tr>
<td>Other (absorbing dye; catalyst; electrolyte</td>
<td>N/A</td>
</tr>
<tr>
<td>Total</td>
<td>23.40</td>
</tr>
</tbody>
</table>

Cost calculations have large degree of uncertainty

- Materials cost alone are significant

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<td>Flexible encapsulant</td>
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<td>Surlyn</td>
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<td>Packaging material</td>
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<td>N/A</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>23.40</td>
</tr>
</tbody>
</table>

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

### Vacuum Sublimation
- Only small molecules
- Layers made by sublimation of material in vacuum
- Easy access to multi-layer systems
- High material purity

Rene Janssen, today 13:20
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: $\approx 10$ 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
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)

- Anode (e.g. ITO)
- Cathode (e.g. Al)
- Donor
- Acceptor

Energy loss is unavoidable!

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)
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.

<table>
<thead>
<tr>
<th>Device type</th>
<th>PCE (%)</th>
<th>$J_{SC}$ (mA cm$^{-2}$)</th>
<th>FF (%)</th>
<th>$V_{OC}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>8.24</td>
<td>15.4</td>
<td>70.6</td>
<td>0.759</td>
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<tr>
<td>Inverted</td>
<td>9.15</td>
<td>17.2</td>
<td>72.0</td>
<td>0.740</td>
</tr>
<tr>
<td>Inverted, tested by CPVT</td>
<td>9.214</td>
<td>17.46</td>
<td>69.99</td>
<td>0.754</td>
</tr>
</tbody>
</table>

Z. He et al., Nature Photonics 6, 591 (2012)
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- **Materials requirements for organic solar cells**
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- 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

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 (bimolecular) recombination

via CT state:

- $\beta$ constant
- $\beta_L(\mu)$ Langevin
- $\beta'_L(\mu)$ mod. Lang.
Direct recombination, without Langevin mechanism

selective contacts: direct recombination, constant $\beta$

$\eta [%]$

$\mu_p [\text{cm}^2/\text{Vs}]$ $10^{-2}$ $10^{-4}$ $10^{-6}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $10^0$ $10^2$

$\mu_n [\text{cm}^2/\text{Vs}]$

(a)

Direct recombination, with Langevin mechanism

New Small Molecule Absorber Materials


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The thiophene zoo...

<table>
<thead>
<tr>
<th></th>
<th>3T</th>
<th>4T</th>
<th>5T</th>
<th>6T</th>
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<tr>
<td>H</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<tr>
<td>Me</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
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<tr>
<td>Et</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
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<tr>
<td>Bu</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
</tbody>
</table>

University of Ulm
Department Organic Chemistry II
Energy Levels vs. backbone length

\[ \text{DCVnT: Fitzner et al., AFM 21, 897 (2011)} \]

\[ \text{DCVnT-Bu: Schüppel et al., PRB 77, 085311 (2008)} \]
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 $j_{(-1V)}/j_{sc}$

$V_{oc} = 1.13 \text{ V}$
$V_{oc} = 1.00 \text{ V}$
$V_{oc} = 0.93 \text{ V}$

$FF = 27.6\%$
$FF = 50.4\%$
$FF = 49.7\%$

$\frac{j_{(-1V)}}{j_{sc}} = 1.32$
$\frac{j_{(-1V)}}{j_{sc}} = 1.10$
$\frac{j_{(-1V)}}{j_{sc}} = 1.15$

*decreases* with increasing chain length

Minimum exciton separation loss is approx. 0.3 eV

ITO / Au(1) / pTNATA(30) / pNPD(10,4:1) / NPD(5) / DCVnT (8) / C\textsubscript{60} (40) / Bphen(6) / Al(100)
New Thiophenes: DCV5T-Me Series

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

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

3: DCV5T-Me(3,3)

Absorbance [normalized] vs. Wavelength [nm]

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\textsubscript{60} (2:1 v/v) blend layers fabricated by coevaporation on glass substrates at 90 °C, with the pattern for pristine C\textsubscript{60} shown for comparison.
The p-i-n Concept for Organic Solar Cells

4P-TPD

Di-NPD

2-TNATA

F4-TCNQ

AOB

C60

ZnPc

DCV5T-Bu

M. Riede et al., Nanotechnology 19, 424001 (2008)
DCV5T-Me Results

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

<table>
<thead>
<tr>
<th>#</th>
<th>$V_{oc}$ (V)</th>
<th>$I_{sc}$ (mA/cm²)</th>
<th>FF</th>
<th>Eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.91</td>
<td>9.6</td>
<td>62.5</td>
<td>5.5</td>
</tr>
<tr>
<td>2</td>
<td>0.95</td>
<td>9.4</td>
<td>62.1</td>
<td>5.6</td>
</tr>
<tr>
<td>3</td>
<td>0.96</td>
<td>11.1</td>
<td>65.6</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Materials:
- ND9P (1)
- Au (50nm)
- BPAPF (5)
- DCV5T-Me 1-3:C$_{60}$ (2:1, 90°C, 30)
- C$_{60}$ (15)
- glass + ITO
The DCV5T-Me story revisited... (Chris Elschner et al.)

- almost identical molecular structure
- identical stack

DCV5T-Me(3,3) [D33] 6.9%

DCV5T-Me(1,1,5,5) [D15] 4.8%
GIWAXS single layers
glass / DCV5Ts (30 nm)

- 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

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

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

- morphology changes:
  - crystallinity
  - roughness
  - OSC efficiency

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

Temperature Levels:
- RT
- intermediate temp.
- high temp.

Graph:
- g l a s s \ D 1 5 : C 6 0 (2:1) RT
- g l a s s \ D 1 5 : C 6 0 (2:1) 90 °C
**Interpretation**

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

**Intermediate temp.**
- morphology changes:
  - crystallinity
  - roughness
  - OSC efficiency

**High temp.**
- surface segregation of DCV → crystallinity → roughness → OSC efficiency

\[ [D15] > 110^\circ \text{C} \]
\[ [D33] > 80^\circ \text{C} \]
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
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%

<table>
<thead>
<tr>
<th>e.gap (eV)</th>
<th>Optical Gap (nm)</th>
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<tbody>
<tr>
<td>first cell</td>
<td>second cell</td>
</tr>
<tr>
<td>1.9</td>
<td>1.25</td>
</tr>
<tr>
<td>770</td>
<td>1300</td>
</tr>
<tr>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td>690</td>
<td>1030</td>
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<tr>
<td>2.225</td>
<td>1.7</td>
</tr>
<tr>
<td>645</td>
<td>890</td>
</tr>
</tbody>
</table>

T. Mueller et al.
Pin-tandem cells: doped layers are critical for optical optimization

• 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)
- 74 nm (1st min)
- 124 nm (2nd max)
Pin-tandem cells: placing absorbers in different field maxima

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 $V_{oc}$

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

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

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

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

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%

<table>
<thead>
<tr>
<th></th>
<th>$V_{oc}$ [V]</th>
<th>$j_{sc}$ [mA cm$^{-2}$]</th>
<th>FF [%]</th>
<th>mismatch</th>
<th>Intensity [mW cm$^{-2}$]</th>
<th>$\eta$ [%]</th>
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<tbody>
<tr>
<td>F4-ZnPc-device</td>
<td>0.66</td>
<td>8.3</td>
<td>64</td>
<td>0.99</td>
<td>100</td>
<td>3.9</td>
</tr>
<tr>
<td>DCV6T-device</td>
<td>0.88</td>
<td>8.3</td>
<td>66</td>
<td>1.08</td>
<td>111</td>
<td>4.3</td>
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<tr>
<td>Tandem 60nm</td>
<td>1.53</td>
<td>3.2</td>
<td>74</td>
<td>–</td>
<td>$98^*$</td>
<td>3.6$*$</td>
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<tr>
<td>Tandem 165nm</td>
<td>1.52</td>
<td>5.0</td>
<td>71</td>
<td>–</td>
<td>$98^*$</td>
<td>5.6$*$</td>
</tr>
</tbody>
</table>
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

9.7 % on 1.1cm² certified by Fraunhofer ISE, Germany
Small-Molecule OPV Record > 1cm²

12% Efficiency - new world Record for OPV
Measured by SGS at standard test conditions (December 2012)
9% Module Efficiency on Glass
Record efficiencies thanks to minimum upscaling losses

<table>
<thead>
<tr>
<th>7 Cells in Series</th>
<th>Active Area</th>
<th>Total Area</th>
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<tbody>
<tr>
<td>VOC</td>
<td>11.8 V</td>
<td>11.8 V</td>
</tr>
<tr>
<td>VOC per cell</td>
<td>1.67 V</td>
<td>1.67 V</td>
</tr>
<tr>
<td>JSC mA/cm²</td>
<td>1.21</td>
<td>1.04</td>
</tr>
<tr>
<td>FF</td>
<td>63 %</td>
<td>63 %</td>
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<tr>
<td><strong>Efficiency</strong></td>
<td><strong>9.0 %</strong></td>
<td><strong>7.7 %</strong></td>
</tr>
</tbody>
</table>

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

Amorphous Si single layer
Dye sensitized
Small area "hero" OPV
Certified >1cm² OPV

diagram available under www.orgworld.de
Organics is more: The O-Factor

• Standard measurement: 1 sun, 25 °C, perpendicular incidence

• Reality: 40-60 °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
**Incident Angle Performance**

**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)

Due to O-Factor:
Performance of a-Si is matched already with 8.3% technology!
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Lifetime measurements


- 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

Dependence of degradation on photocurrent

- Degradation is directly proportional to photocurrent

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)
Results of degradation study

- 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

<table>
<thead>
<tr>
<th>Stress Conditions</th>
<th>Device Temperature</th>
<th>Integrated Light Dosis</th>
<th>Corresponding Exposure Time in Middle Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50°C</td>
<td>8.1 MWh/m²</td>
<td>8 y</td>
</tr>
<tr>
<td></td>
<td>85°C</td>
<td>dark</td>
<td></td>
</tr>
</tbody>
</table>
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’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 reliability lab measurement of BDR-based stack, 80 cm² active area
Heliatek Roll coater
Roll-to-Roll Vacuum Coater

- 14 Linear Organic Evaporators
- DC-Magnetron
- Lineare Ion Source
- Interleaf Winder
- Substrate Winder
- Port for Inert Substrate Load
- Lock
- 2 Metal Evaporators
- 3-color-white pin OLED
WHITE PIN OLED

Transparent OLED on Polymer web

top emitting OLED on metal sheets
Conclusions

- 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
• K. Fehse C. May, C. Kirchhof, M. Toerker, M. Hoffmann, S. Mogck, C. Lehmann, T. Wanski (FhG-IPMS)
• J. Blochwitz-Nimoth, J. Birnstock, T. Canzler, S. Murano, M. Vehse, M. Hofmann, Q. Huang, G. He, G. Sorin (Novaled)
• M. Pfeiffer, B. Männig, G. Schwartz, K. Walzer (Heliatek)
• J. Amelung, M. Eritt (Ledon)
• D. Gronarz (OES)

• R. Fitzner, E. Brier, E. Reinold, A. Mishra, P. Bäuerle (Ulm)
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