Organic solar cells – are 20 yrs of lifetime realistic

Ch. J. Brabec
EMPA Workshop: Durability of thin film solar cells

- **Introduction:**
- **Lifetime:**
- **Mechanisms:**
- **Field test:**
- **Summary**

**Organic Photovoltaics**

- State of the Art
- Intrinsic semiconductor degradation
- Imaging the degradation of solar cells
Introduction: Organic solar cells

Organic Solar Cells is one technology among organic electronics

- use of abundant raw materials
- potentially cheap
- potentially flexible
- potentially printed

pictures: Novaled, Konarka, Leo
Introduction: Organic solar cells

Organic Solar Cells are at market entry

- Developments driven by OLED/ lighting
- .... than photovoltaics
- .... than electronics
**Introduction: Organic solar cells**

Organic Electronics is based on $\pi$ conjugated, excitonic semiconductors

- $sp^2$ hybridized carbon bonds
- works for small molecules, polymers, ...

![Diagram of Organic Electronics](image-url)
Introduction: Organic solar cells

Most famous representatives come from the carbon allotropes

- $sp^2$ hybridized carbon bonds
- works for Carbon Allotropes ...

Stable semiconductors, metals – or ballistic conductors

- fairly mature for parent fullerenes
- ample room for derivatives

extremely high RT-charge carrier mobilities of $\mu \geq 200,000$ cm$^2$/Vs

outstanding electronic and mechanical properties discovered

ground breaking electronic properties of single sheets

ultrastrong materials, semiconductors, metals

e-acceptor components, neuroprotectants, superconductors, magnets
**Introduction: Organic solar cells**

π conjugated semiconductors are excitonic in nature

- Binding energy of $\sim 300$ meV
- Requires heterojunction for photogeneration of charges
\( \pi \) conjugated semiconductors are excitonic in nature

- Binding energy of \( \sim 300 \) meV
- Requires heterojunction for photogeneration of charges
Introdução: células solares orgânicas

As células solares orgânicas requerem DOIS semicondutores para a geração de carregamento.

- Um tipo p
  - P3TBT, $E_g = 1.90 \text{ eV}, 4.2\%$
  - PCPDTBT, $E_g = 1.46 \text{ eV}, 5.5\%$
  - PSBTBT, $E_g = 1.47 \text{ eV}, 5.2\%$
  - PBTDPP2, $E_g = 1.40 \text{ eV}, 4.4\%$
  - PDPP3T, $E_g = 1.30 \text{ eV}, 4.7\%$
  - PCDTBT, $E_g = 1.85 \text{ eV}, 6.0\%$
  - HXS-1, $E_g = 1.95 \text{ eV}, 5.4\%$
  - PBTTT-C, $E_g = 1.61 \text{ eV}, 6.6\%$

- Um tipo n

Brabec et al., AM 2011
Li et al., 2011, Phys Chem Phys
Introduction: Organic solar cells

π conjugated semiconductors require TWO heterojunctions

- One for charge generation
Introduction: Organic solar cells

π conjugated semiconductors require TWO heterojunctions

- One for charge separation – at the interface
- Results in two architectures: normal and inverted

Pictures courtesy D. Olson, NREL
Waldauf et al. JAP 2006
Introduction: Organic solar cells

Organic solar cell efficiency – more than 1000 structures published

- More than 40 structures with performance beyond 5%
Introduction: Organic solar cells

Organic solar cell efficiency – certified at > 10 %

- Performance comparable to DSSC or a-Si
Organic solar cell efficiency – certified at > 10 %

- 3 different systems (1 single junction, 2 tandem junction) certified ~ 10 %
Organic solar cells – why do we need another technology?

- Technology at 0.1 €/Wp
- Production in Europe
- Ultralow investments
- Production on demand
- Abundant materials
- Green production
Organic solar cells – it is about the printing, not the organics!

- High productivity
- Low investment
- Production on demand
- Low Capex

BUT

- This becomes only relevant for a TW scenario
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➤ Introduction: Organic Photovoltaics

➤ Lifetime: State of the Art

➤ Mechanisms: intrinsic semiconductor degradation

➤ Field test: Imaging the degradation of solar cells

➤ Summary
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Reviewing State of the Art:

- Unpackaged devices: NREL data
- Glass packaged devices: Heliatek
- Flex packaged modules: Konarka Technologies
Unpackaged systems

- P3HT:PCBM – normal vs inverted devices
- Lifetimes as short as 10 hours for unstable normal architecture
Unpackaged systems

- Interface degradation is dominating
- Explained by pin-hole formation and passivation of interface
Unpackaged systems

- dense composite electrodes increase lifetime > 5000 hrs, 1 sun
- WVTR of electrode $\sim 10^{-3}$ g/m$^2$d or better required
Glass packaged systems

- Heliatek – glass packaged tandem modules
- Latest data: *extrapolated* +30 years of lifetime (ISOS3 protocol)
Glass packaged systems

- glass – glass packaging: > 10000 hrs stability under 1 sun
- WVTR of glass package $\sim 10^{-5}$ g/m$^2$d
Flex packaged systems

Lowell, MA

Southern Florida

Lowell, MA

Southern Arizona
Flex packaged systems – outdoor testing

> 3 years outdoor lifetime reported (under various conditions)

TÜV Rheinland certified IEC 61646 for Konarka flex modules

Correlation between ALT and outdoor is missing!
OPV lifetime – HERO DATA

Unpackaged devices with wrong architecture die within 10 hours

Same / similar semiconductors are stable in optimized architectures:

- 5000 hrs lightsoaking, unpackaged
- 30 yrs predicted for glass packaged (extrapolated from)
- > 10 yrs predicted for flex package
- Passed IEC 61646, flex modules
- 3 yrs outdoor reported

Lifetime is a function of packaging – WVTR < 10^{-3} desired
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Intrinsic & Extrinsic degradation

- At least 9 processes were suggested leading to device degradation
OPV Lifetime: Intrinsic degradation

How to distinguish between intrinsic & extrinsic degradation

- How to distinguish between semiconductor and interface degradation?
- Investigate glass – glass packaged devices!
- Understand burn-in defect

![Chemical structures and efficiency graph](image)
OPV Lifetime: *Intrinsic degradation*

**Intrinsic semiconductor degradation**

- Identification or deep traps as main degradation path
- Fairly easy to identify via transport measurements

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*Peeters et al. Thesis (2011)*
**Inert degradation**
- X-Ray, jV, SCLC, EQE, PDS
- reveals trap formation

**Photooxidation**
- UV/Vis, PL, ToF-SIMS, FTIR, ..... 
- Reveals degradation products
- Not relevant for good packages

C. Peeters et al, AEM (2011)
Egelhaaf et al, Chem Mater (2011)
Krebs, AEM (2012)
Gregoryan et al, SOLMAT (2011)
Organic solar cell degradation – intrinsic vs extrinsic mechanisms

- **Intrinsic**: Deep trap formation under inert conditions – relevant for OPV lifetime
- Impurities like residues from polymerization
- Crosslinking, secondary reactions

- **Extrinsic**: OSC are sensitive to photooxidation – irrelevant for good package
- Kinetics of photooxidation not well understood
- Catalytical role of water appears essential
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Imaging defects in PV power plants by IR

Inspection by Drone IR images
→ Localizing string defects on a cell level
Imaging Analysis: visualization methods

- Imaging defects – what are we looking for

  - Light beam induced current (LBIC)
  - Lock-in Thermography (LIT)
  - Electroluminescence (EL)

- Shunts
- Electrodes / bus bar failure
  - Cell breakage
  - Delamination
  - Interface failure
Lock-In IR Thermography

Visualizing Shunts AND series/contact resistances

Diode

\[ j \quad \text{[A/cm}^2\text{]} \]

\[ V \quad \text{[V]} \]

- dark
- illuminated

- Voc = 627 mV
- \( j_{sc} = 7.18 \text{ mA/cm}^2 \)
- ff = 55%
- efficiency = 2.46%

Bachmann et al, SOLMAT, 2010
Hoppe et al, JAP, 2010
Photocurrent Imaging

EL imaging and LBIC imaging are fairly identical
EL Imaging

Visualizing Shunt, Series Resistance and Contact Resistance

Requires knowledge of the replacement circuit

Bachmann et al, SOLMAT, 2010
Hoppe et al, JAP, 2010
Imaging OPV degradation: Case study

Measurement protocol

- Konarka specifically provided 10s of P3HT / PCBM modules
- measure JV, DLIT (var bias), ILIT, EL - before and after light soaking
- run degradation for ~15 hrs
  - damp heat (85°C / 85 rh), dry (95°C / 5 rh), light (65°C / UV)
- remeasure JV, DLIT (var bias), ILIT, EL before and after current soaking

Rerun for 1000 hrs
# Degradation pattern of OPV: Case study

<table>
<thead>
<tr>
<th>Defect</th>
<th>EL</th>
<th>ILIT</th>
<th>DLIT</th>
<th>IV</th>
<th>Visual</th>
<th>Microscopy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M248 (85/85 T_{244})</td>
<td>M248 (85/85 T_{184})</td>
<td>M248 (85/85 T_{277})</td>
<td>M248 (85/85 T_{184})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module, test, interval</td>
<td>15.45V, 180mA, 5min</td>
<td></td>
<td></td>
<td>V_{OC} = -8V</td>
<td>dark areas at edge of cell</td>
<td>visual delamination</td>
</tr>
<tr>
<td>Measuring parameters</td>
<td>dark areas at edge of cell</td>
<td>dark areas at edge of cell</td>
<td>dark areas at edge of cell</td>
<td>dark areas at edge of cell</td>
<td>visual delamination</td>
<td></td>
</tr>
<tr>
<td>Short description</td>
<td>D05</td>
<td>M251 (85/85 T_{184})</td>
<td>M251 (85/85 T_{227})</td>
<td>M251 (85/85 T_{184})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Information</td>
<td></td>
<td>V_{OC} = -8V</td>
<td>dark areas at edge of cell</td>
<td>dark areas at edge of cell</td>
<td>visual delamination</td>
<td></td>
</tr>
</tbody>
</table>

## Further information

<table>
<thead>
<tr>
<th>Specification</th>
<th>Delamination of encapsulation foil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visualization method</td>
<td>EL, IR, visual</td>
</tr>
<tr>
<td>Depiction</td>
<td>Bubbles of Gas or Fluid at the edge of the cells to the encapsulation which results in delamination</td>
</tr>
<tr>
<td>Consequence</td>
<td>Inactivity of the regarding cell regions</td>
</tr>
<tr>
<td>Cause</td>
<td>Water and air is entering through the encapsulation into the module</td>
</tr>
<tr>
<td>Appearance/Frequency</td>
<td>4 of 11 Modules</td>
</tr>
</tbody>
</table>
Degradation pattern of OPV: Case study

Degradation processes in P3HT / PCBM modules

1. Missing electrode  **Irrelevant**
2. Layer tear off  **Irrelevant**
3. Bus bar defects – impurities  **Irrelevant**
4. Semiconductor layer impurities  **Irrelevant**
5. Shunts  **Irrelevant**
6. Semiconductor degradation  **Irrelevant**
7. Packaging defects  **relevant**
   - Diffusion of water
   - 2nd diode degradation
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- **OPV**: The importance is the printing

- **OPV Lifetime**: +30 yrs for glass (extrapolated, ISOS 3)
  +10 yrs for film (extrapolated, ISOS 3)
  IEC 61646 passed for flex technology

- **SC Degradation**: intrinsic: trap formation (relevant)
  extrinsic: photooxidation (not relevant today)

- **Field test**: Interface degradation is most relevant

- **Summary**: Lifetime is a function of packaging
Will organic solar cells give + 20 yrs of lifetime

- Probably Yes

Would it be smart to think about business models requiring less than +20 yrs of lifetime

- Probably Yes
Degradation pattern of OPV: Acknowledgement

- Lifetime: Konarka

- Materials: DFG (SPP1355, Exc. Cluster), BMBF, EC (FP VII), CUT, FFG

- Technology: DFG, BMBF, BMU, EC (FP VII)

- Process: State of Bavaria (StWiV)
That was a long story...

Thank you for your attention!