Status and Potential of Organic Solar Cells

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Institut für Angewandte Photophysik (IAPP)

- University institute
- Founded 1908
- Until 1990 mainly work on photography

Present Topics:
- Organic thin films
  Semiconductor Properties/Devices
  Optical Properties
  Epitaxy
- Femtosecond spectroscopy
  on semiconductors (e.g., Bloch oscillations)
- Raster scanning microscopy
  STM/AFM, SNOM

approx. 130 employees (9 funded by university)
(http://www.iapp.de)
Overview

• Working Principles of Organic Solar Cells

• Current Research Challenges

• Beyond 10% Efficiency
## Comparison of typical Semiconductors

<table>
<thead>
<tr>
<th>Property</th>
<th>Germanium</th>
<th>Anthracene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Weight</td>
<td>72.63</td>
<td>178.22</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>937</td>
<td>217</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>5.3</td>
<td>1.28</td>
</tr>
<tr>
<td>Density (molecules/cm³)</td>
<td>4.42x10²²</td>
<td>0.42x10²²</td>
</tr>
<tr>
<td>Crystal Structure</td>
<td>Diamond</td>
<td>Monoclinic</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>16</td>
<td>3.2</td>
</tr>
<tr>
<td>e-Mobility at 300K (cm²/Vs)</td>
<td>3800</td>
<td>1.06</td>
</tr>
<tr>
<td>h-Mobility at 300K (cm²/Vs)</td>
<td>1800</td>
<td>1.31</td>
</tr>
<tr>
<td>Concentration of intrinsic carriers (cm⁻³)</td>
<td>5.2x10¹³</td>
<td>~10⁻⁴</td>
</tr>
<tr>
<td>Vacuum Ionisation Energy (eV)</td>
<td>4.8</td>
<td>5.8</td>
</tr>
</tbody>
</table>

What makes Organic Solar Cells special?

- Photon absorption does not directly generate free charge carriers, but excitons
- Diffusion length of excitons is much smaller than penetration depth of photons

Excitonic Solar Cells

S. E. Gledhill et al., J. Mat. Res. 20, 3167 (2005)
P. Würfel, CHIMIA 61, 770 (2007)
Brief History and Main Concepts

- First Breakthrough 1986: **Donor-Acceptor Heterojunction**
- Second Breakthrough early 1990s: Bulk Heterojunction Concept

Light-weight, cheap, flexible, large area, long-living and efficient solar cells

Optional: colour-tunable and/or semitransparent

Reasons:

• Flexible plastic substrates and thin organic layers
  → Little material and energy consumption
  → Short energy payback time

• Compatible with cheap and large area production technologies

• Toolbox of organic chemistry

• Little restrictions on required materials

Images: Konarka, Neuber, Heliatek, IAPP
Classification of Organic Solar Cells

Solution-Processing
- Mainly polymers, but also small molecules and inorg. materials
- Layers made by e.g. printing
  - High production speeds possible
  - Room temperature process

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

Dye Sensitized Solar Cells (DSSC) aka “Grätzel Cells”
- (nano-)porous TiO$_2$ layers coated with dye
- Layers made by (screen) printing
Typical Stack for solution-processed Organic Solar Cells

- PEDOT:PSS (~40nm)
- Donor:Acceptor (~100-300nm)
- PEDOT:PSS (~40nm)
- ITO-Anode (~120nm)
- Al-Cathode (~100nm)
- glass substrate

Image: Royal Society of Chemistry
p-i-n Stack for vacuum-processed Organic Solar Cells

4P-TPD (HTL)

Di-NPD (HTL)

2-TNATA (HTL)

F4-TCNQ (p)

AOB (n)

C60 (A/ETL)

ZnPc (D)

DCV5T-Bu (D)

M. Riede et al., Nanotechnology 19, 424001 (2008)
Advantages of molecular Doping

- Active Fermi level control in HTL/ETL
- Quasi-Ohmic Contact to electrodes
- Conductivity increase by several orders of magnitude

→ Freedom of stack design

M. Riede et al., Nanotechnology 19, 424001 (2008)
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- Working Principles of Organic Solar Cells
- Current Research Challenges
- Beyond 10% Efficiency
Current Research Challenges

- Improving the device efficiency $\eta$
  - $V_{oc}$ $\leftarrow$ HOMO$_D$-LUMO$_A$ offset
  - $J_{sc}$ $\leftarrow$ Absorption gap
  - FF $\leftarrow$ Barriers & transport

- Increasing device lifetime

$$\eta = \frac{V_{oc} \cdot J_{sc} \cdot FF}{P_{ill}}$$
Tuning the Open Circuit Voltage $V_{oc}$: Examples

- Donor Side
  - DCV6T
  - DCV5T

- Acceptor Side

$\Delta HOMO_D \rightarrow \Delta V_{oc}$

$\Delta LUMO_A \rightarrow \Delta V_{oc}$

R. Fitzner et al., Adv. Funct. Mat. 21, 897 (2011)
$J_{sc}$ and FF: the Influence of Morphology

- Homogeneous mixture & smooth surface at RT
- Increased structure size, higher surface roughness
  ➔ Enhanced phase separation → better transport
**J_{sc}** and FF: the Influence of Morphology

Sun simulator: Steuernagel (SoCo-1200MHG)
Measurement conditions: T~32°C, intensity calculated according to mismatch
Device area: 6.4mm²

Efficiency Predictions for Single Heterojunction OPV

ΔE_{LUMO}

E_g

LUMO

HOMO

Donor

Acceptor


G. Dennler et al., Adv. Funct. Mat. 21, 1323 (2009)
Overview

• Working Principles of Organic Solar Cells

• Current Research Challenges

• Beyond 10% Efficiency
Beyond 10% Efficiency

- Much of the solar spectrum not used!
- Narrow absorption → absorption losses
- Wide absorption → thermalisation losses
Tandem Solar Cells

Goal:
• to exceed the single heterojunction limit

Requirements:
• Efficient recombination contact
• Current matching
• Complementary absorption

M. Riede et al., Nanotech. 19, 424001 (2008)
Efficient Recombination Contact

→ highly transparent recombination contact without loss of $V_{oc}$

Current Matching and Complementary Absorbers

Oligothiophene derivative (Heliatek)

Red dye (BASF)

Absorber 1:C60

p-HTL Spacer

Absorber 2:C60

ITO

glass substrate

Al

Organic based Photovoltaics

absorption (normalized)

Oligothiophene derivative (Heliatek)

Red dye (BASF)

wavelength / nm

400 500 600 700 800 900

0.0 0.2 0.4 0.6 0.8 1.0
Current Matching and Complementary Absorbers

Absorber 1: C60
Absorber 2: C60
p-HTL Spacer

Measurement calibrated with aperture; area used for calculations: 7.1 mm²
Device Lifetime of a 6% Tandem Stack

May 2009 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>

Data by Gregor Schwartz
OPV World Record $> 1\text{cm}^2$

8.3 % on 1.1cm$^2$ certified by Fraunhofer ISE, Germany
• Results are obtained within a co-operation between Heliatek and IAPP
• The device uses proprietary absorber materials developed and synthesised by Heliatek and C60
• It is based on Heliatek’s p-i-n tandem solar cell technology using p- and n-dopants provided by Novaled AG

Results are highly reproducible
Development of OPV Efficiencies in the Laboratory

Conversion efficiency (\%) vs Year

1985 - 2015

- a-Si stabilized
- Dye sensitized "Grätzel cell"
- Small area "hero"
- All solid state polymer + small molecule

Companies:
- Solarex
- EPFL
- Sharp
- United Solar
- Konarka
- Heliatek/IAPP
- Solarmer
- Pletronics
- Princeton
- Kodak
- UCSB
- UCambridge
- ULinx
- (c) K. Leo/IAPP

Area >1cm²
Quo Vadis?

- Device lifetime sufficient for first applications
- Little material consumption (<1g/m²)
- In principle no material bottleneck for organic materials
- Large area fabrication possible

Images: Konarka, COMEDD, Heliatek
Summary

• Many organic semiconductors available

• Little material and energy consumption during production

• High stability for small molecule 6% tandem devices

• Champion lab efficiencies above 8%

• OPV at the step towards products

• Next step: transfer to low cost, large area manufacturing…
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€:

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Thank you for your attention!

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