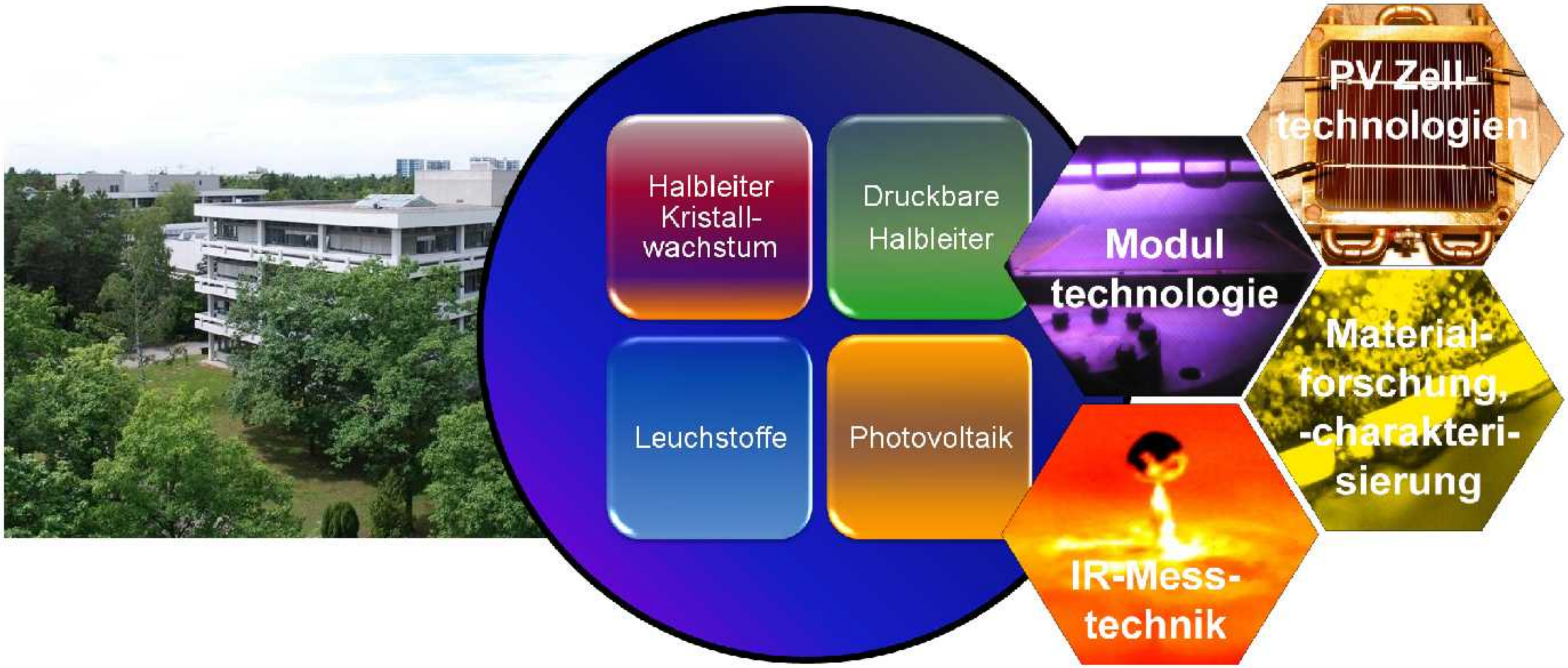
Organic solar cells – are 20 yrs of lifetime realistic

Ch. J. Brabec



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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

Introduction: *Organic solar cells*

Organic Solar Cells is one technology among organic electronics

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

Organic materials

Organic light emitting diodes

Photovoltaic cells

Transistors and memory

pictures: Novaled, Konarka, Leo

Organic Solar Cells are at market entry

- Developments driven of by OLED / lighting
- …. than photovoltaics
- …. than electronics

4th wave:
Organic electronics

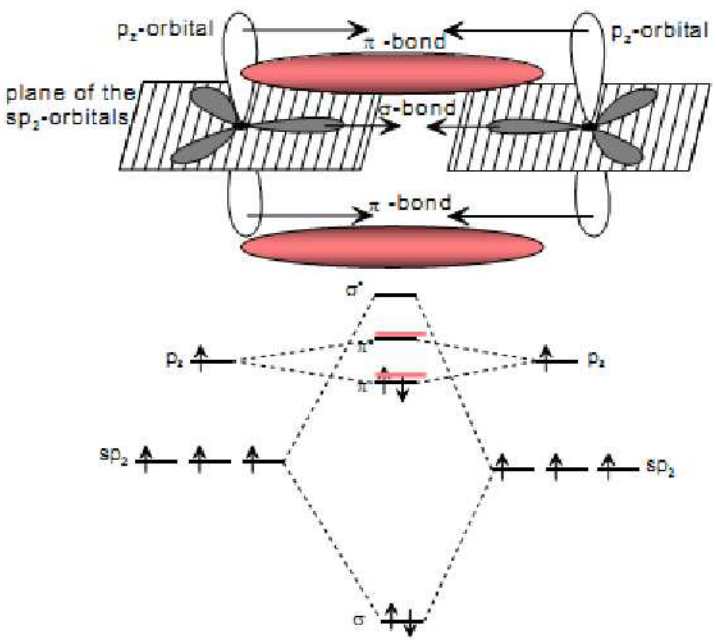
3rd wave:
Solar cells

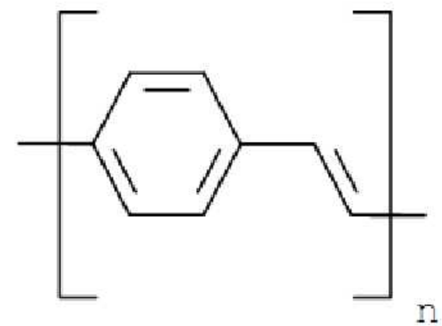
2nd wave:
OLED lighting

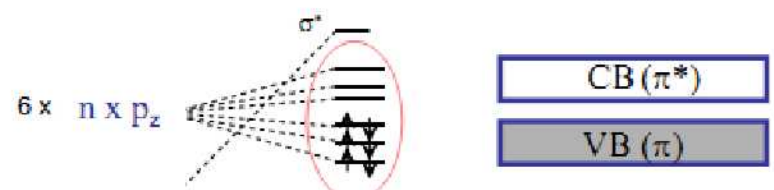
1st wave: OLED
Displays

Organic Electronics is based on π conjugated, exitonic semiconductors

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



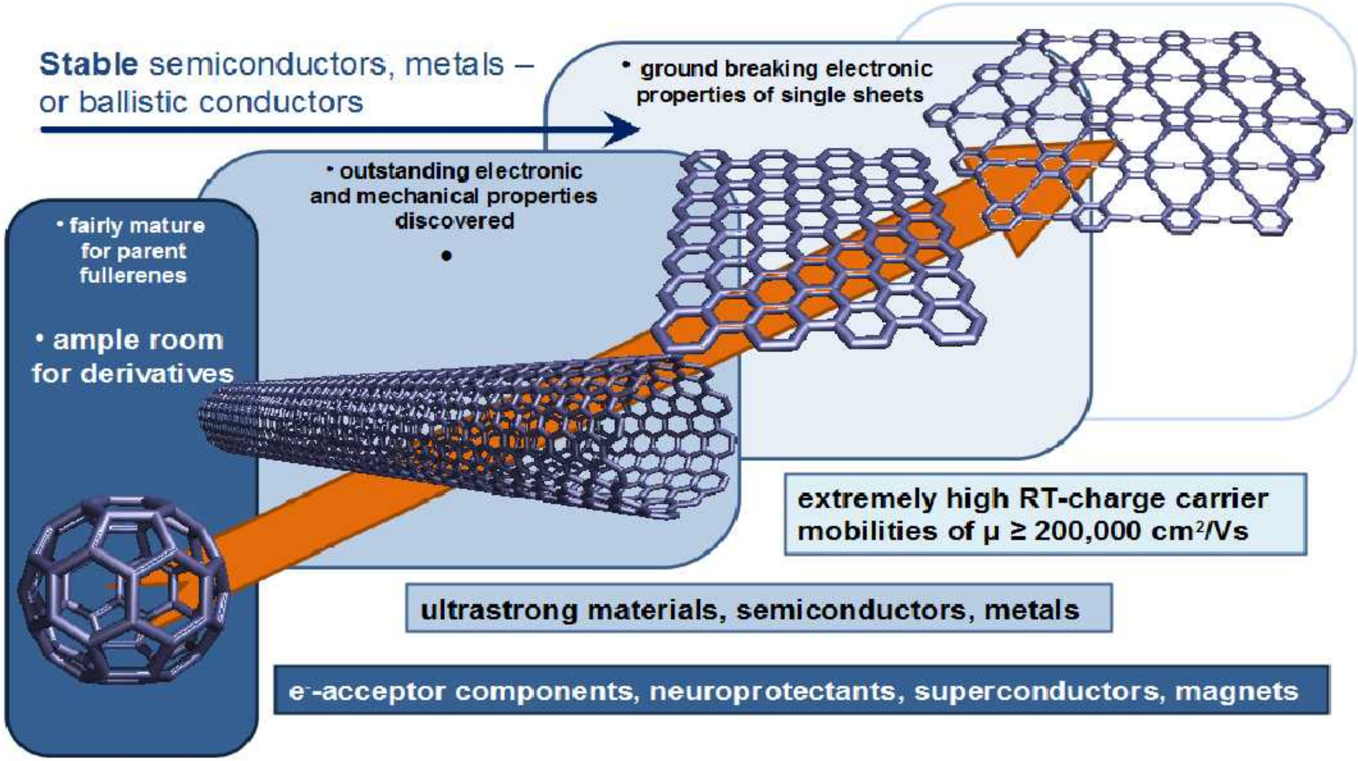




pictures: K. Leo, TU Dresden

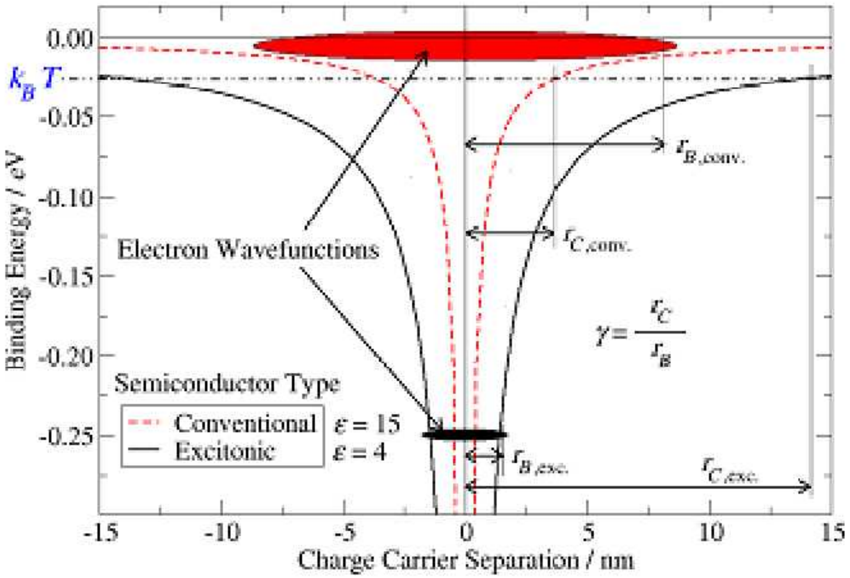
Most famous representatives come from the carbon allotropes

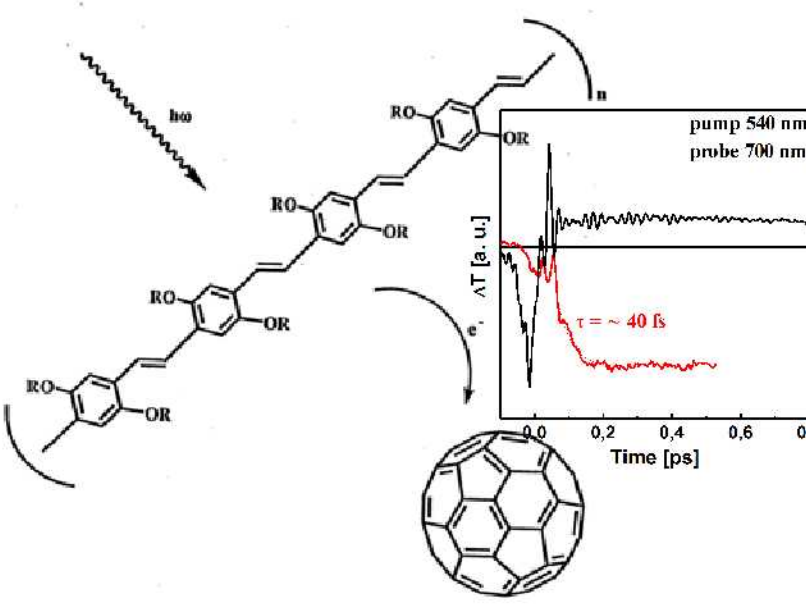
- sp^2 hybridized carbon bonds
- works for Carbon Allotropes …



π conjugated semiconductors are excitonic in nature

- Binding energy of ~ 300 meV
- Requires heterojunction for photogeneration of charges



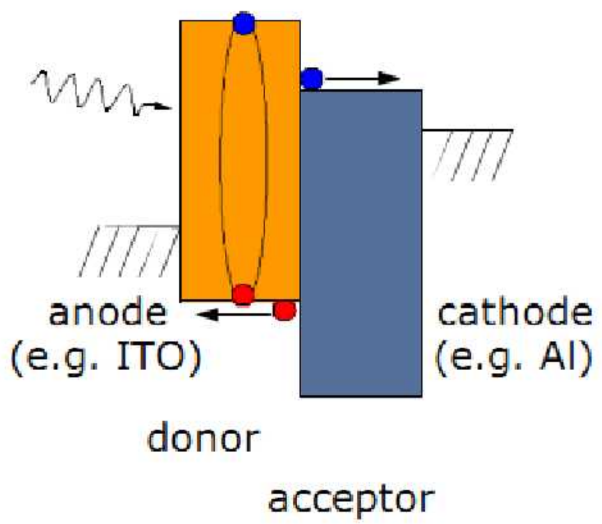


Sariciftci (eds) – Organic Semiconductors (2004)
Würfel, CHIMIA 61, 770 (2007)
Gregg, APL (2005)
Brabec, CPL,(2001)

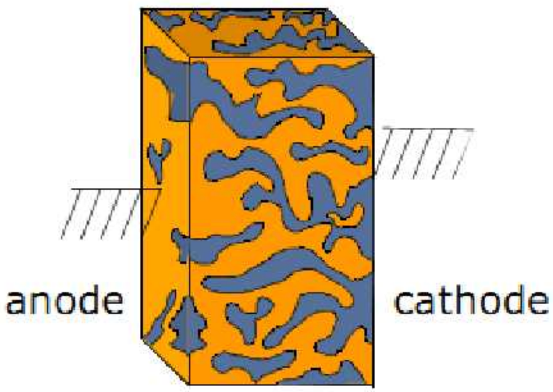
π conjugated semiconductors are excitonic in nature

- Binding energy of ~ 300 meV
- Requires heterojunction for photogeneration of charges

Flat heterojunction (FHJ)



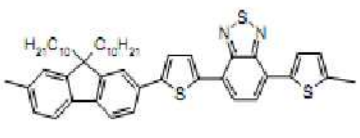
bulk heterojunction (BHJ)



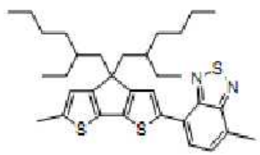
Tang, APL 48, 183 (1986)
Hiramoto, APL 58, 1062 (1991)
Hall, Nature 376, 498 (1995)
Yu, Science 270, 1789 (1995)

Organic solar cells require TWO semiconductors for charge generation

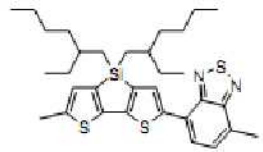
- One p-type



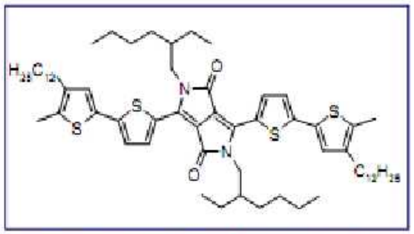
PFTBT, E_g = 1.90 eV, 4.2%



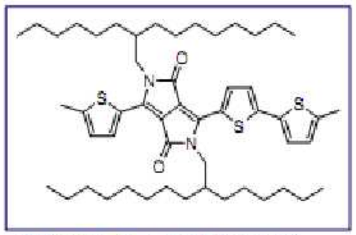
PCPDTBT, E_g = 1.46 eV, 5.5%



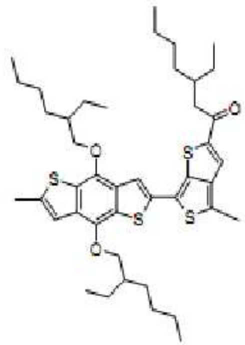
PSBTBT, E_g = 1.47 eV, 5.2%



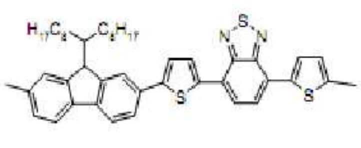
PBBTDPP2, E_g = 1.40 eV, 4.4%



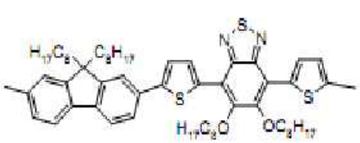
PDPP3T, E_g = 1.30 eV, 4.7%



PBDTTT-C, E_g = 1.61 eV, 6.6%

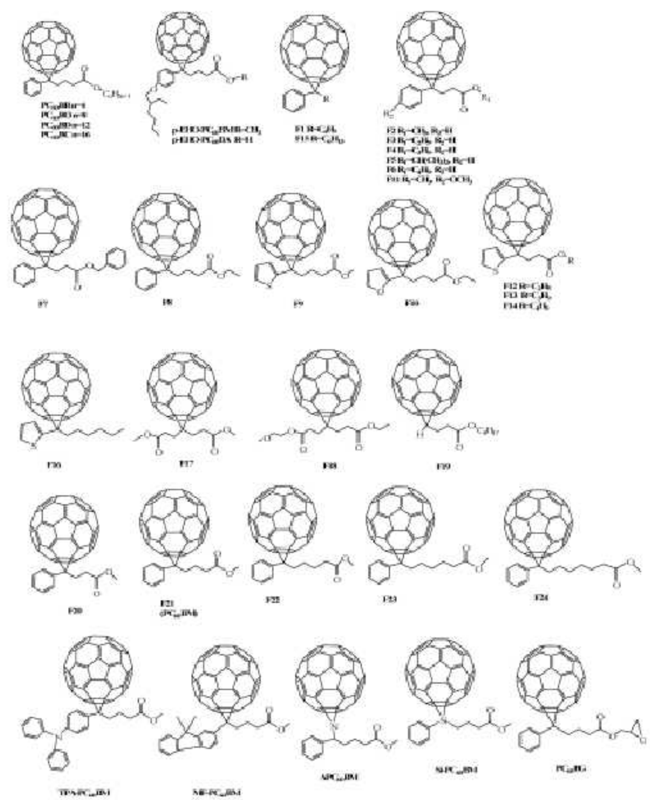


PCDTBT, E_g = 1.85 eV, 6.0%



HXS-1, E_g = 1.95 eV, 5.4%

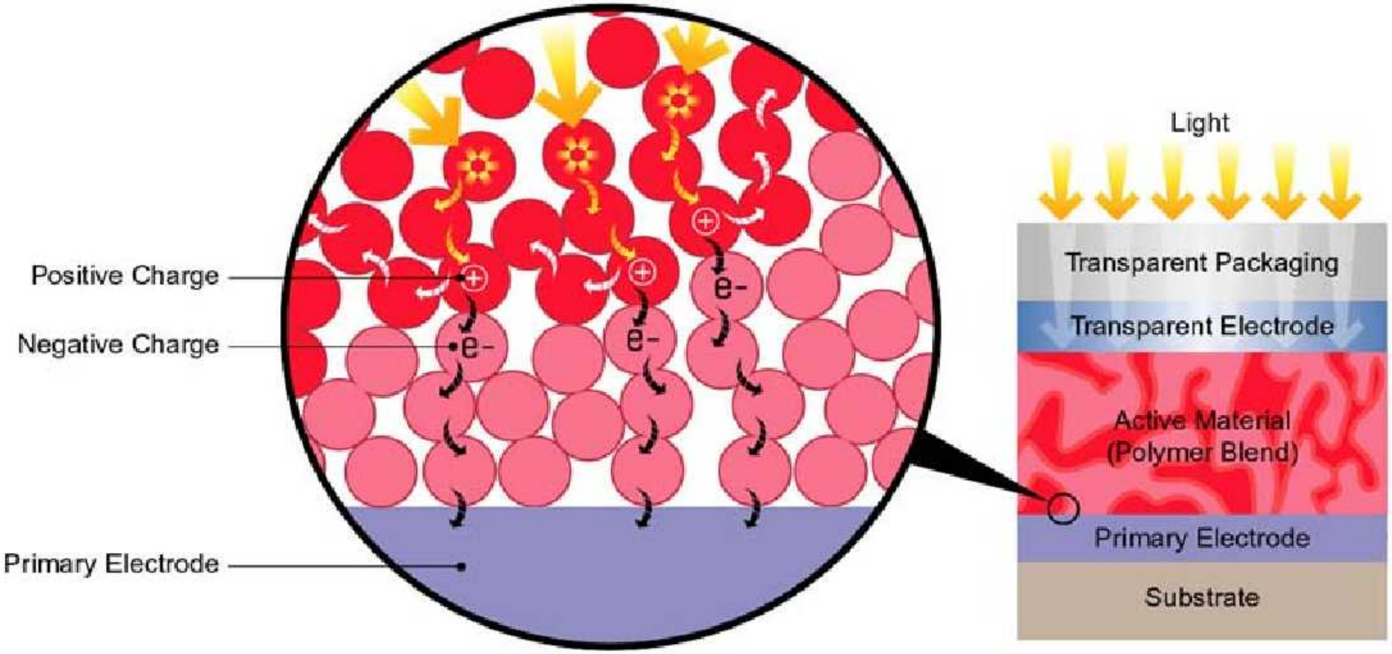
One n-type



Brabec et al, AM 2011
Li et al, 2011, Phys Chem Phys

π conjugated semiconductors require TWO heterojunctions

- One for charge generation



Tang, APL 48, 183 (1986)
Hiramoto, APL 58, 1062 (1991)
Hall, Nature 376, 498 (1995)
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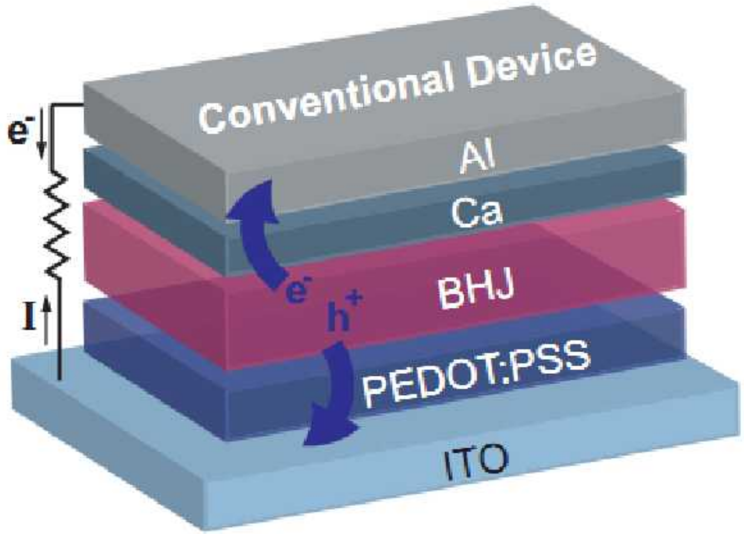
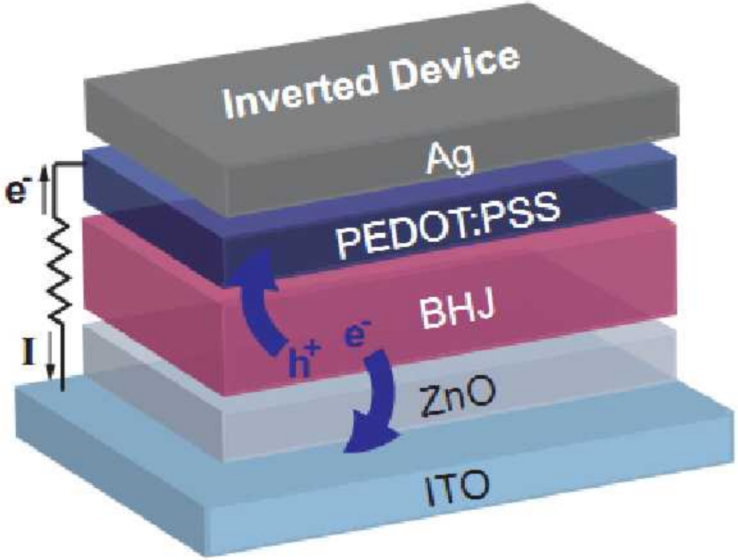
π conjugated semiconductors require TWO heterojunctions

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

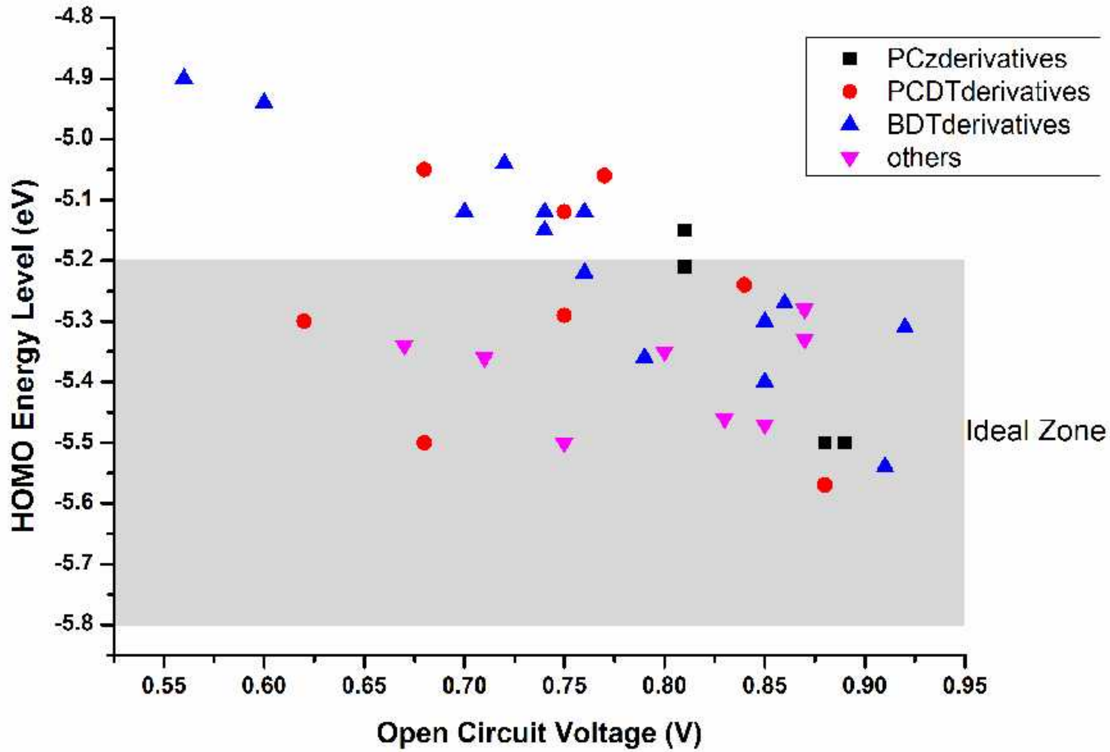




Pictures courtesy D. Olson, NREL
Waldauf et al, JAP 2006

Organic solar cell efficiency – more than 1000 structures published

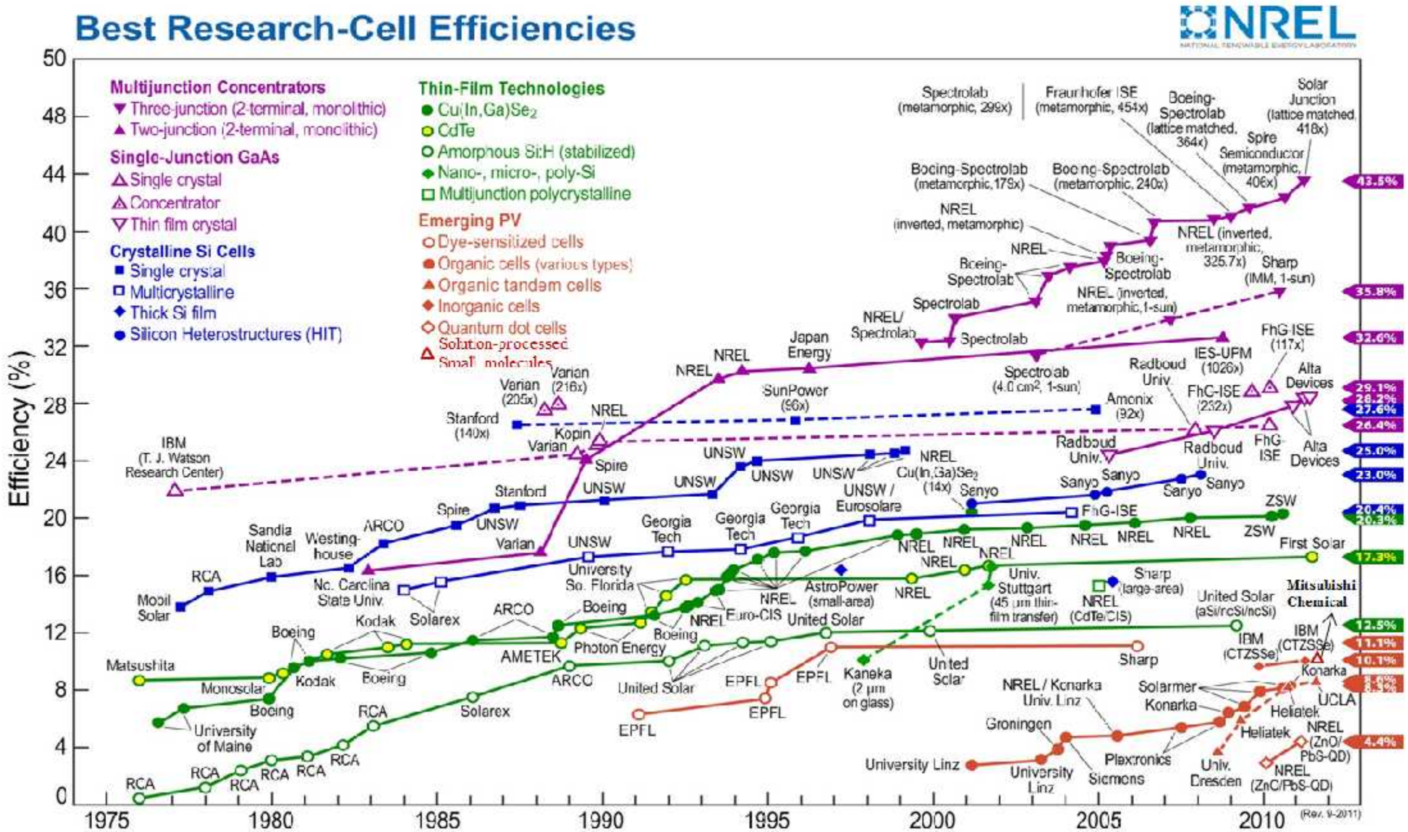
- More than 40 structures with performance beyond 5 %



Baran et al, High efficiency photovoltaics (Springer), 2012

Organic solar cell efficiency – certified at > 10 %

- Performance comparable to DSSC or a-Si



picture – courtesy of NREL

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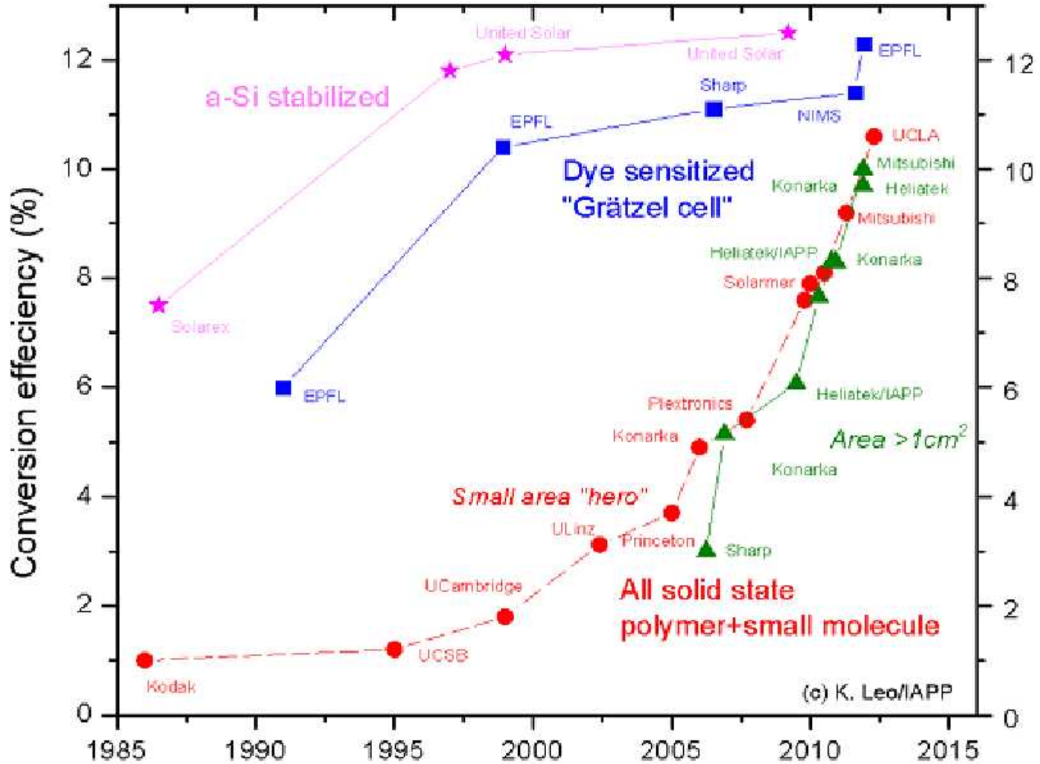
Organic solar cell efficiency – certified at > 10 %

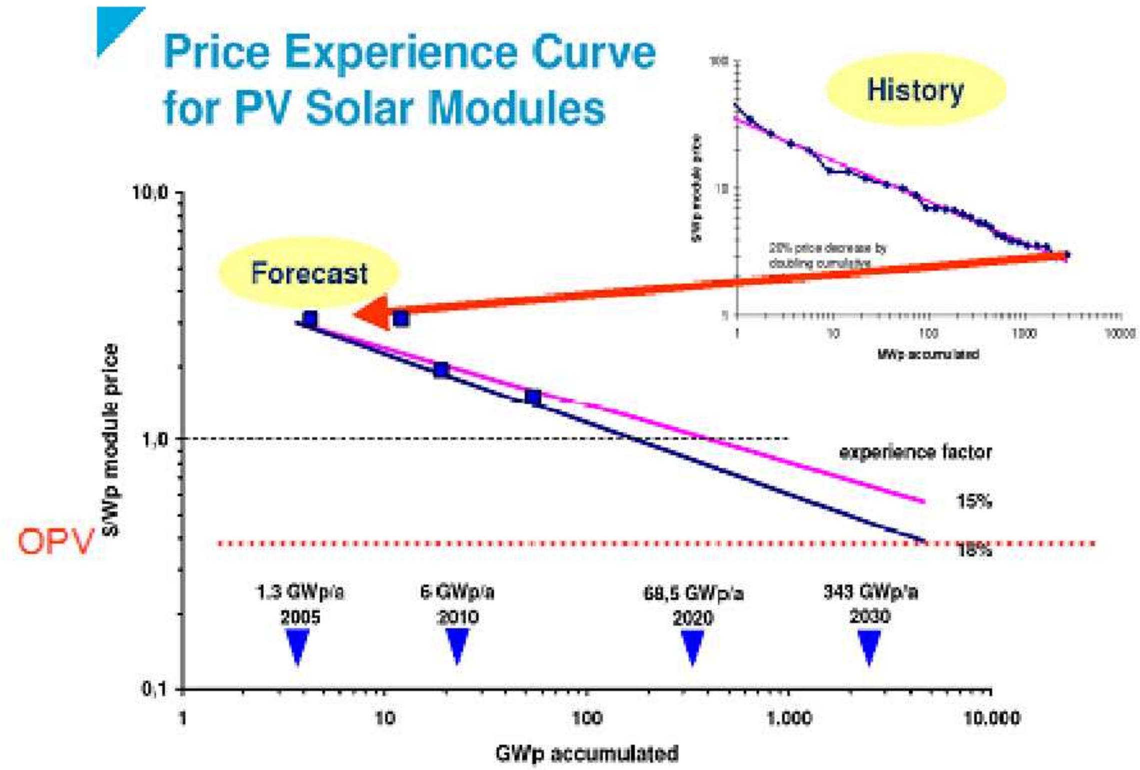
- 3 different systems (1 single junction, 2 tandem junction) certified ~ 10 %



picture – www.orgworld.de

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



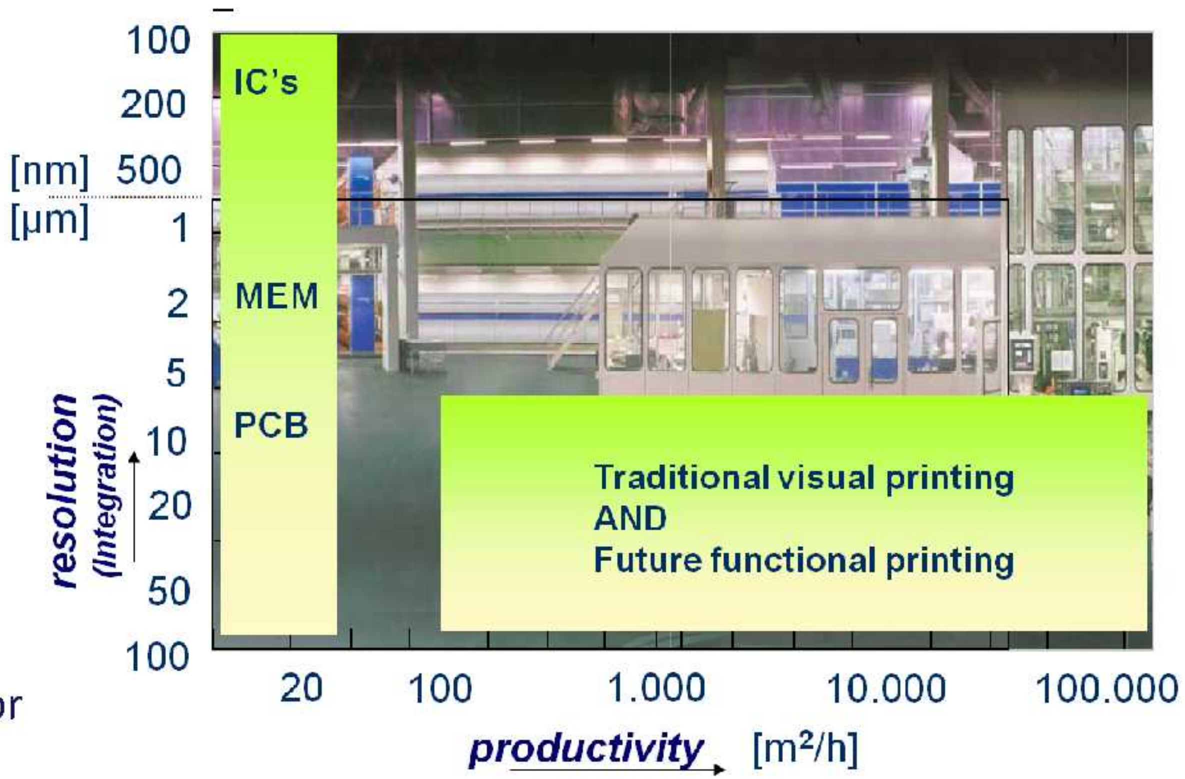
picture – W. Hoffmann

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

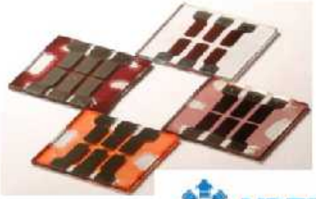


Brabec et al, Organic Photovoltaics, Wiley (2008)

- Introduction: Organic Photovoltaics
- **Lifetime: State of the Art**
- Mechanisms: intrinsic semiconductor degradation
- Field test: Imaging the degradation of solar cells
- Summary

Reviewing State of the Art:

- **Unpackaged devices:** NREL data



- **Glass packaged devices:** Heliatek

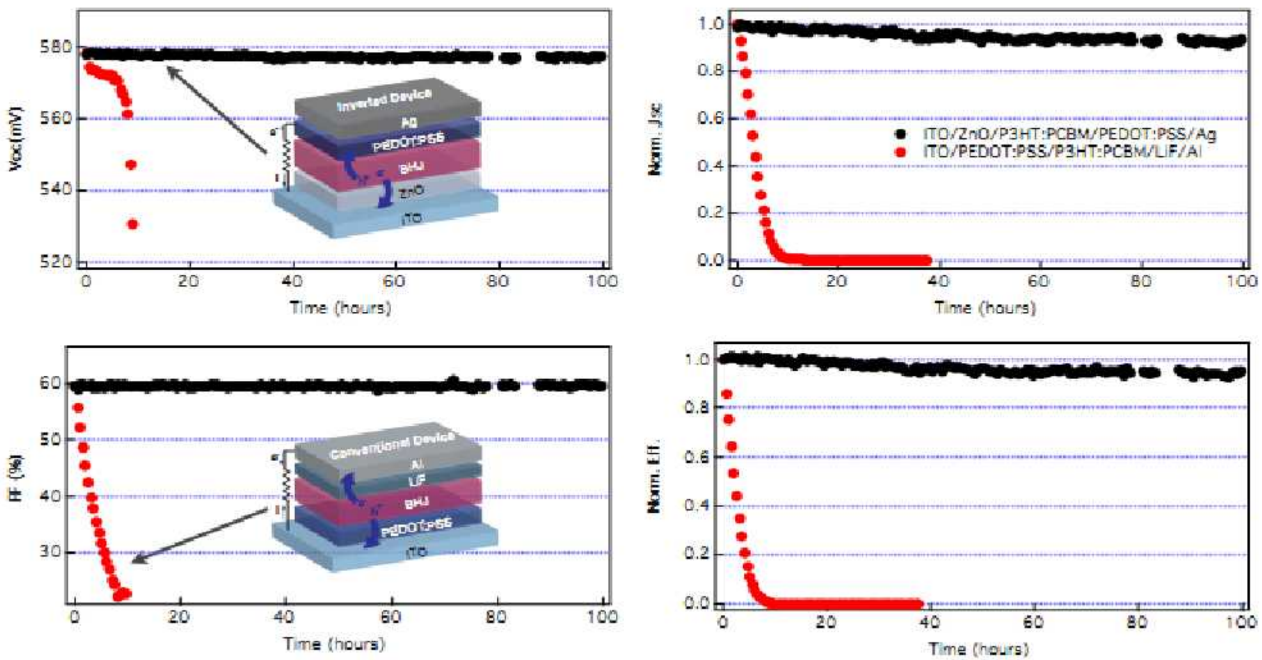
- **Flex packaged modules:** Konarka Technologies

Konarka®

Unpackaged systems

- P3HT:PCBM – normal vs inverted devices
- Lifetimes as short as **10 hours** for **unstable normal arcitecure**

NREL

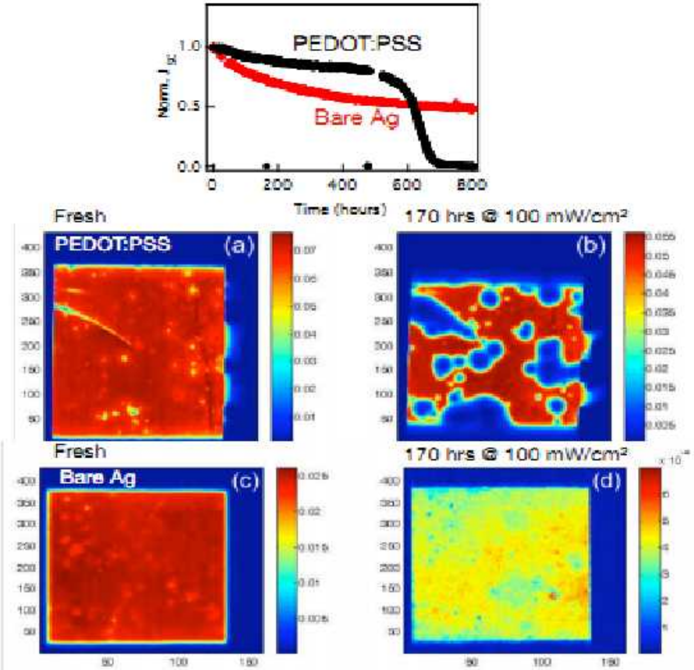


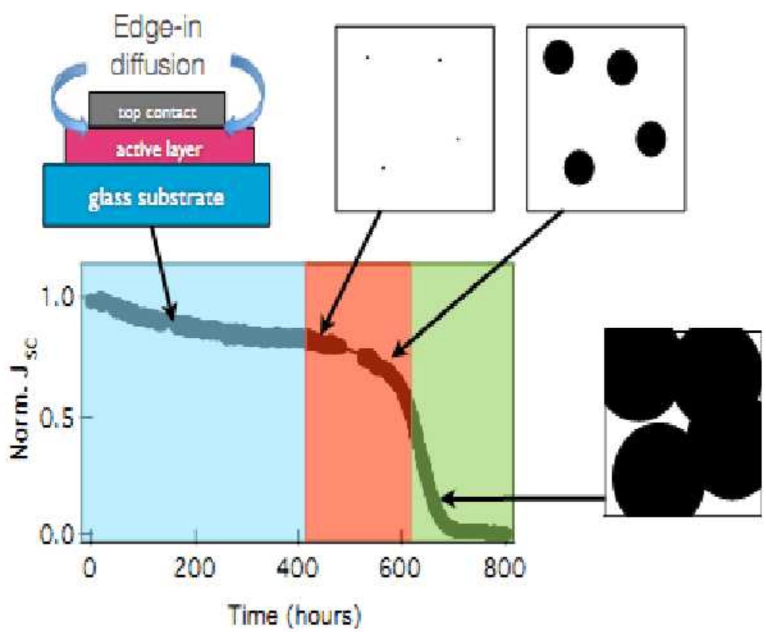
M. Lloyd et al, in print

OPV Lifetime: *State of the Art*

Unpackaged systems

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





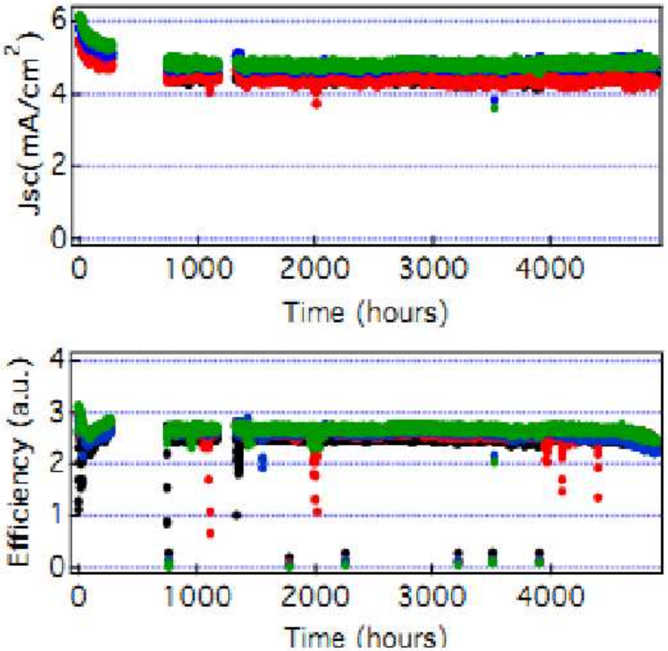
M. Lloyd et al,SOLMAT 2011

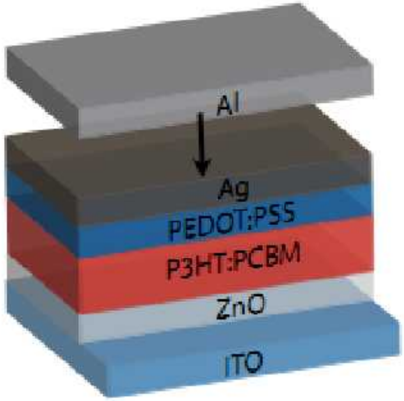
OPV Lifetime: *State of the Art*

Unpackaged systems

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

NREL





M. Lloyd et al, in print

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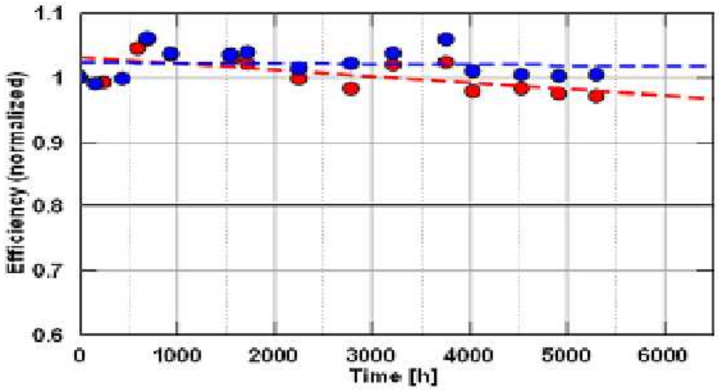
Glass packaged systems

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



Stress Conditions	Device Temperature	Integrated Light Dosis	Corresponding Exposure Time in Middle Europe
🔵	50°C	8.1 MWh/m²	8 y
🔴	85°C	dark	

K. Leo, SPP1355, Würzburg (2011)

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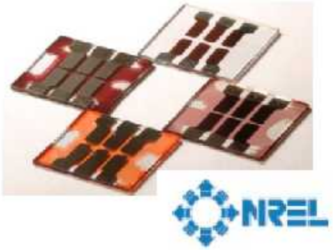
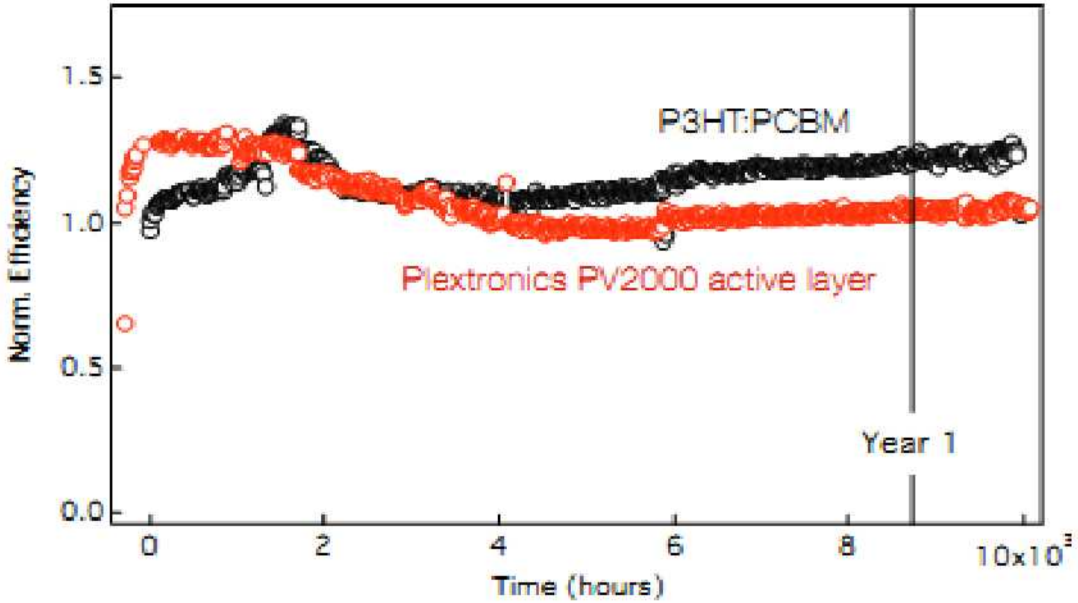
OPV Lifetime: *State of the Art*

Glass packaged systems

- glass – glass packaging: > 10000 hrs stability under 1 sun
- WVTR of glass package ~ 10^{-5} g/m^{2}d





M. Lloyd et al, in print

OPV Lifetime: *State of the Art*

Flex packaged systems

Konarka®

Flex packaged systems – outdoor testing

> 3 years outdoor lifetime reported (under various conditions)

Konarka

TÜV Rheinland certified IEC 61646 for Konarka flex modules

Correlation between ALT and outdoor is missing!

E. Zeira, SPIE 2011, San Diego
Konarka Press Release 2011 / 2012

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

- Introduction: Organic Photovoltaics
- Lifetime: State of the Art
- **Mechanisms: intrinsic semiconductor degradation**
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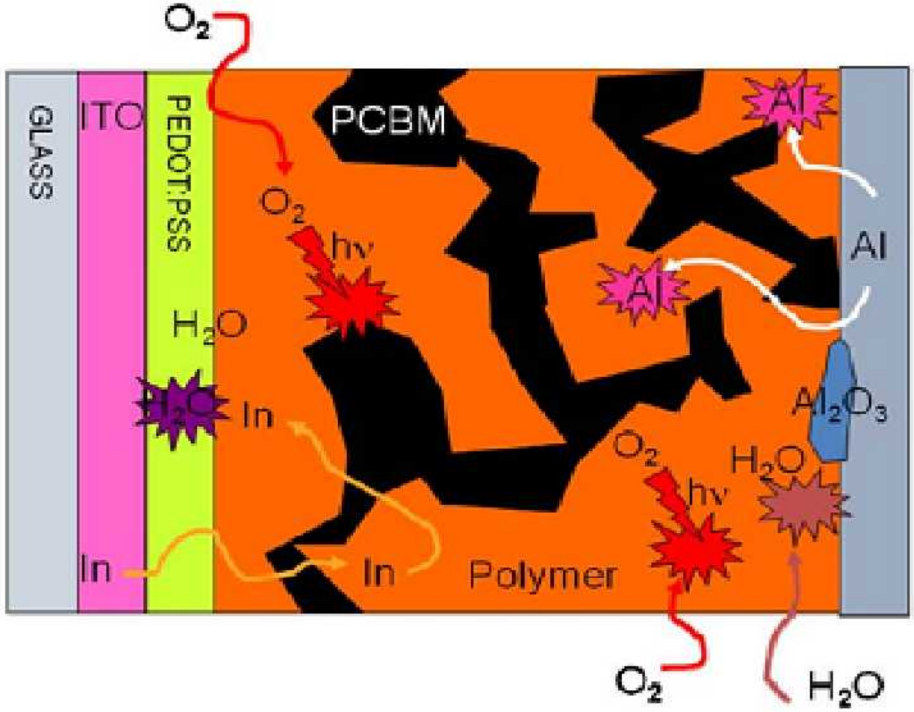
Intrinsic & Extrinsic degradation

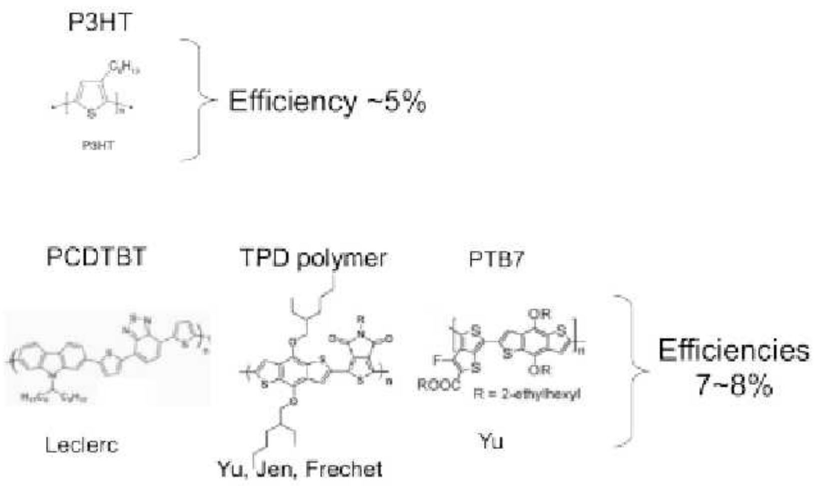
- At least 9 processes were suggested leading to device degradation

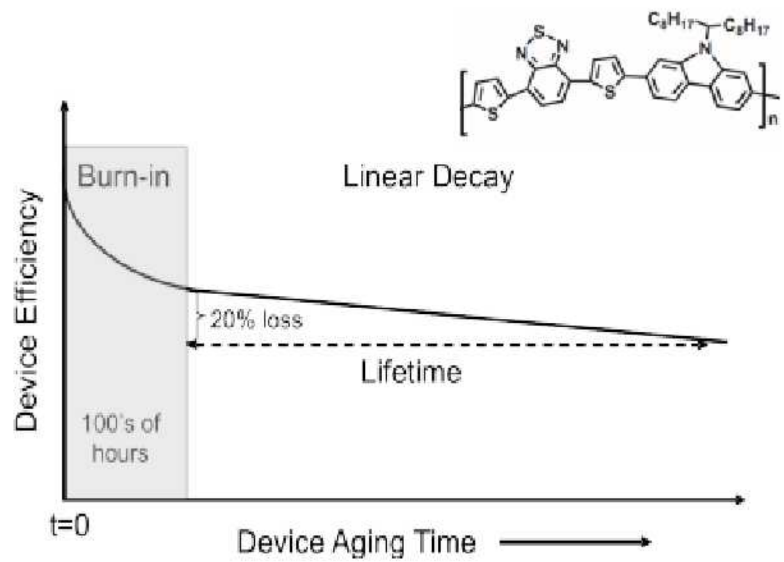


S. Georgyvan et al, presentation SPP1355 (Würzburg, 2011)

How to distinguish between intrinsic & extrinsic degradation

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

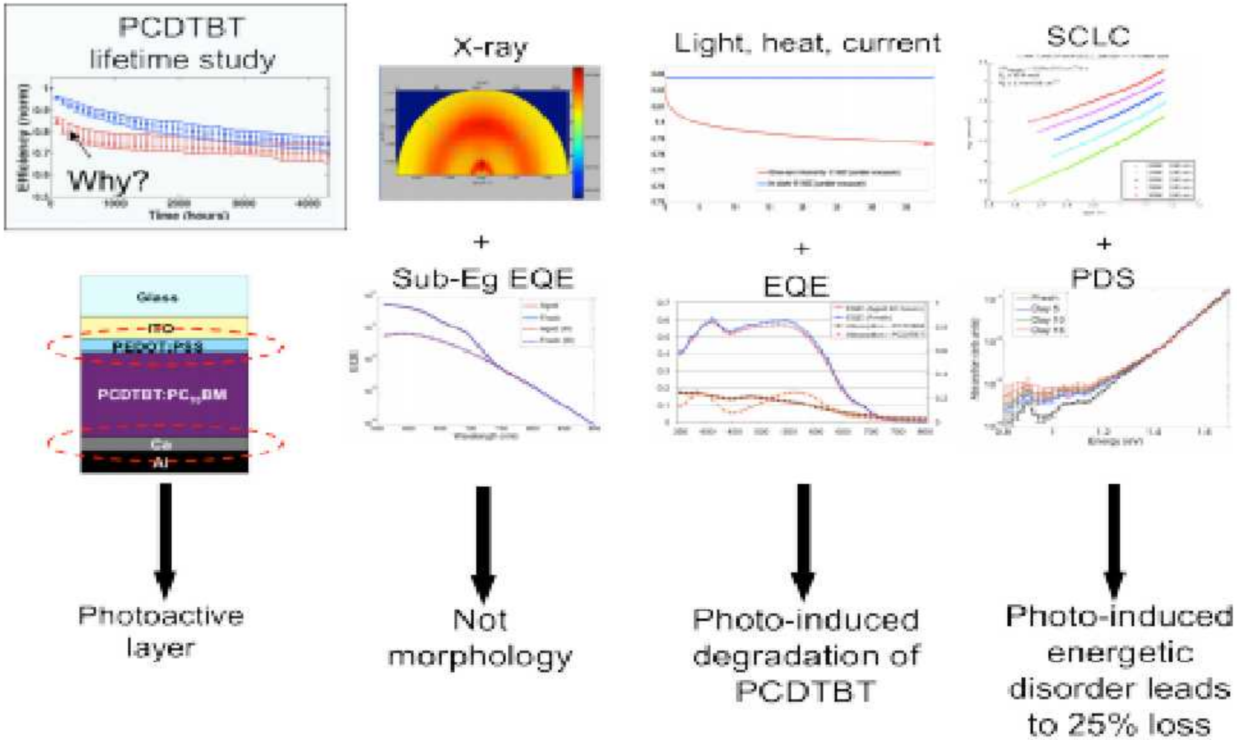




Peeters et al, AEM (2011)

Intrinsic semiconductor degradation

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



Peeters et al, Thesis (2011)

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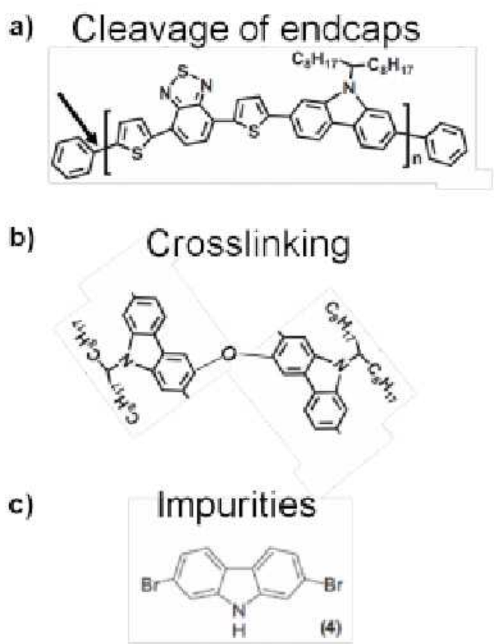
OPV Lifetime: *Intrinsic degradation*

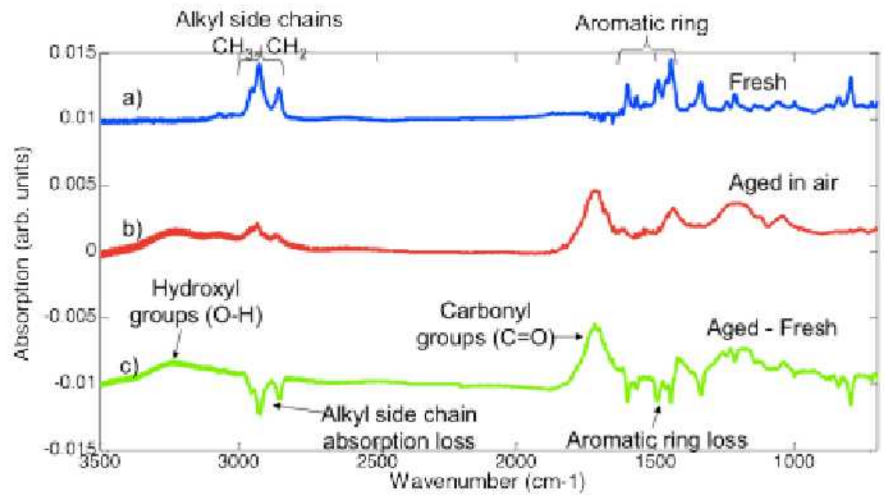
Inert degradation

- 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)
Hintz et al, Chem Mater (2010)
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

- Introduction: Organic Photovoltaics
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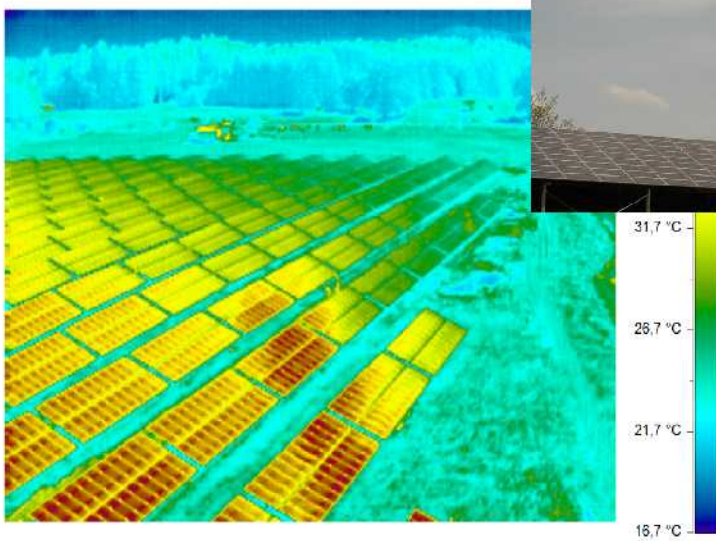
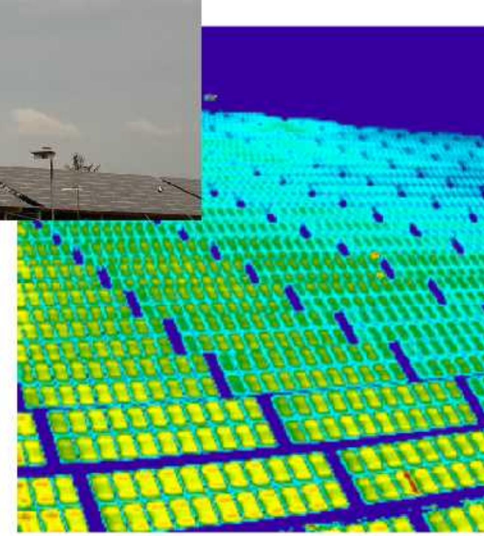
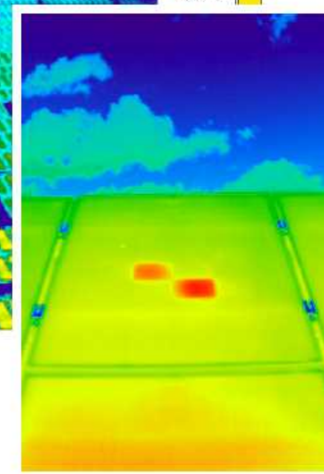
Imaging Analysis: *visualization methods*

Imaging defects in PV power plants by IR





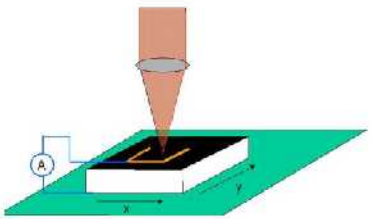


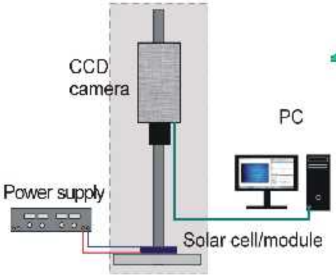
Inspection by Drone IR images
→ Localizing string defects on a cell level

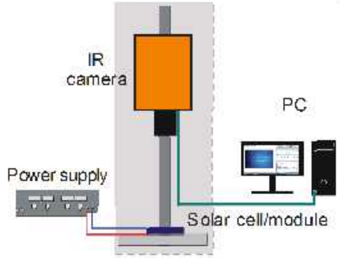
Imaging Analysis: *visualizaton methods*

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

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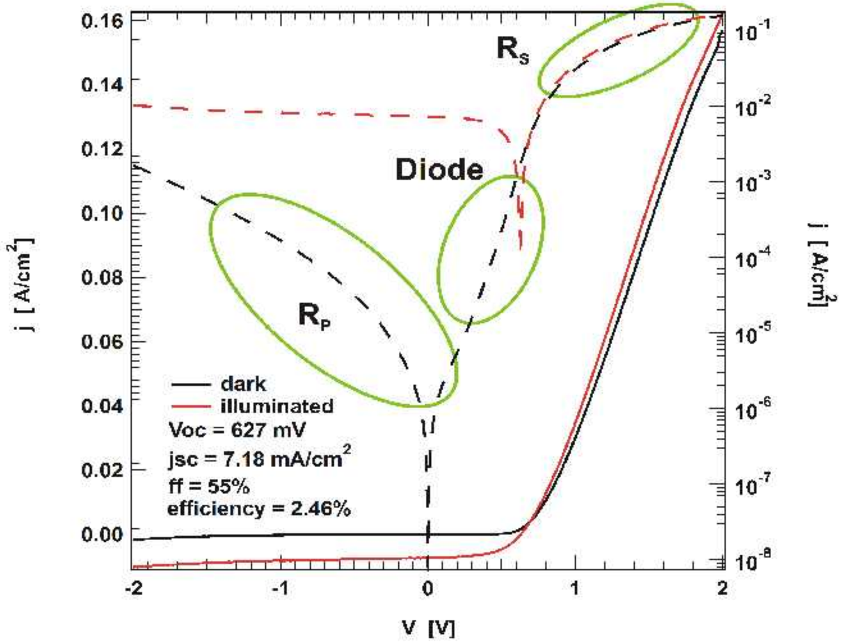
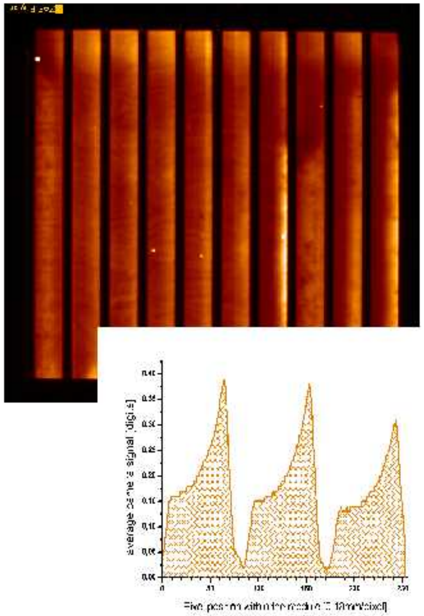
Lock-In IR Thermography

Visualizing Shunts AND series /contact resistances

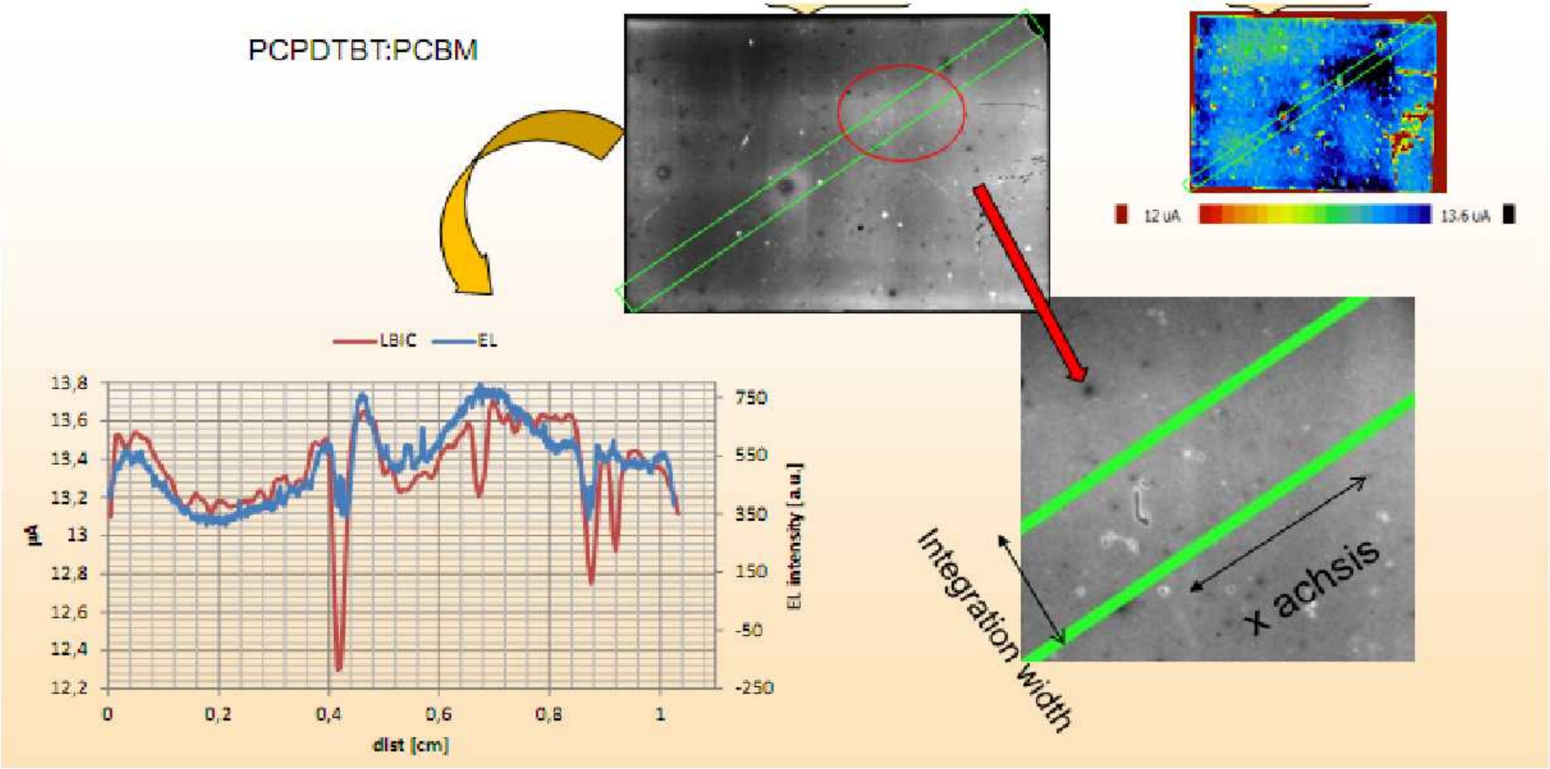




Bachmann et al, SOLMAT, 2010
Hoppe et al, JAP, 2010

Photocurrent Imaging

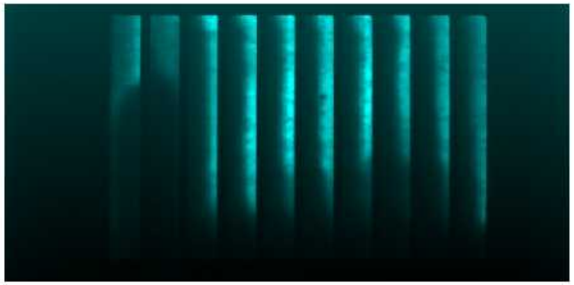
EL imaging and LBIC imaging are fairly identical

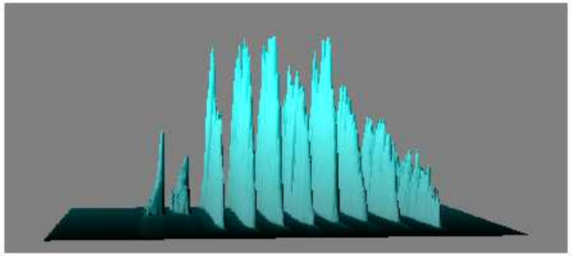


Bachmann et al, SOLMAT, 2010
Hoppe et al, JAP, 2010

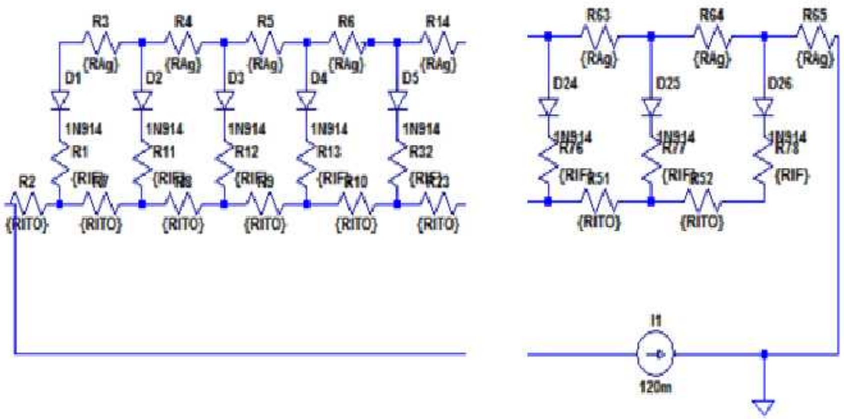
EL Imaging

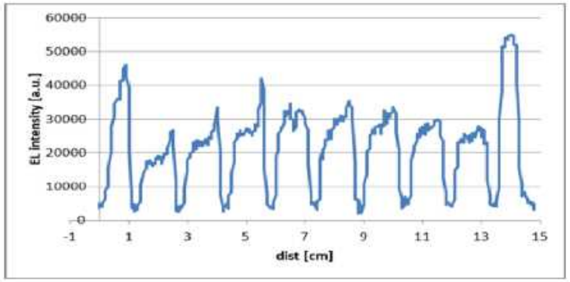
Visualizing Shunt, Series Resistance and Contact Resistance





Requires knowledge of the repalcement circuit





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

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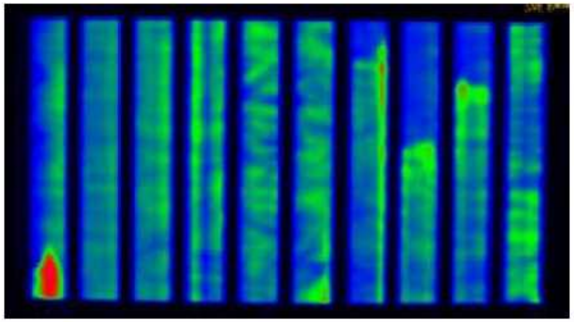
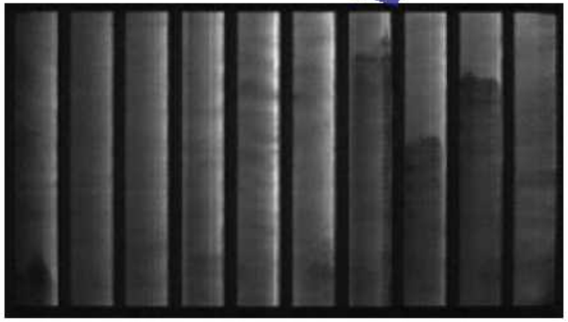
Measurement protocol

- Konarka specifically provided 10s of P3HT / PCBM modules

Rerun for 1000 hrs

- measure jV, DLIT (var bias), ILIT, EL - before and after light soaking
- run degradation for ~ 15 hrs
  - damp heat (85°C / 85 rh), dry heat (85° C/ 5 rh), light (65° C / UV)
- remeasure jV, DLIT (var bias), ILIT, EL before and after light soaking





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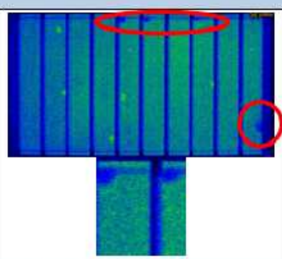
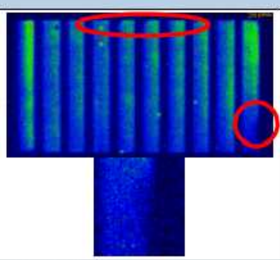
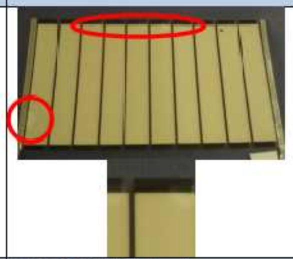
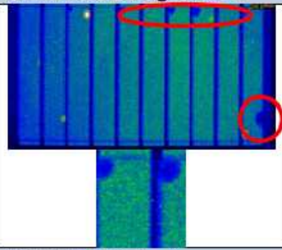
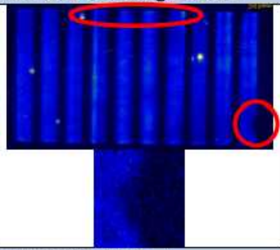
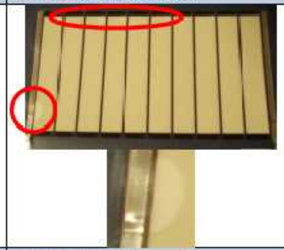
Degradation pattern of OPV: *Case study*

Module, test, interval
Measuring parameters
Short description
Information

Defect	EL	ILIT	DLIT	IV	Visual	Microscopy
						
	M248 (85/85 T_{414})	M248 (85/85 T_{184})	M248 (85/85 T_{227})		M248 (85/85 T_{184})	
	15.45V, 180mA, 5min	V_{OC}	-8V			
	dark areas at edge of cell	dark areas at edge of cell	dark areas at edge of cell		visual delamination	
D05						
		M251 (85/85 T_{184})	M251 (85/85 T_{227})		M251 (85/85 T_{184})	
		V_{OC}	-8V			
		dark areas at edge of cell	dark areas at edge of cell		visual delamination	
	Further information					
	Specification	Delamination of encapsulation foil				
	Visualization method	EL, IR, visual				
	Depiction	Bubbles of Gas or Fluid at the edge of the cells to the encapsulation which results in delamination				
	Consequence	Inactivity of the regarding cell regions				
	Cause	Water and air is entering through the encapsulation into the module				
	Appearance/Frequency	4 of 11 Modules				

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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) Packaing defects - diffusion of water - 2nd diode degradation	relevant

- **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)

Degradation pattern of OPV: *A*cknowledgement

That was a long story…

Thank you for your attention!