Small Molecule Organic Solar Cells – Status and Perspectives

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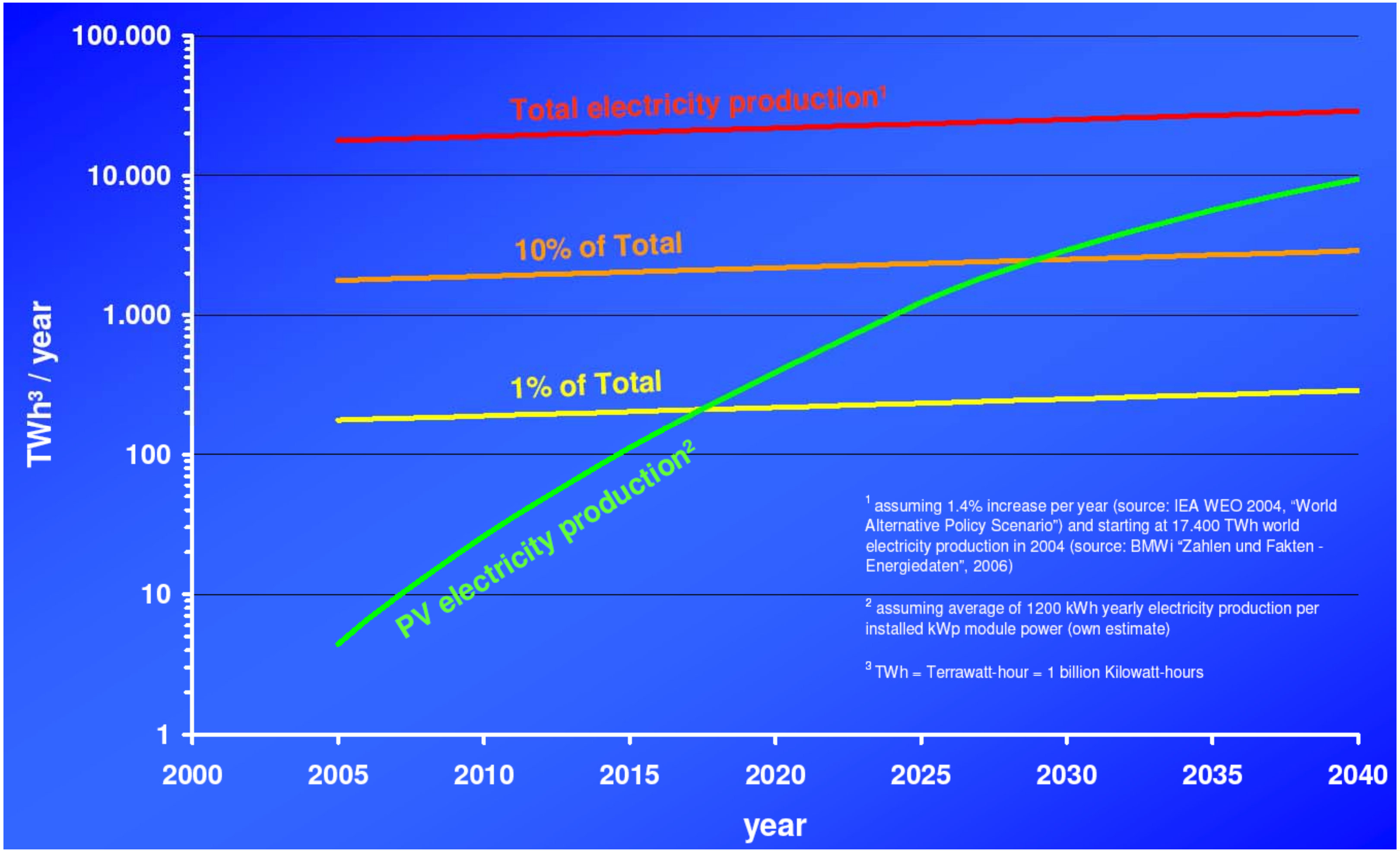
Linz, February 7, 2008

Outline

- Some thoughts about Organic PV in general
- Status of small-molecule organic solar cells:
  key innovations in the past
- Future challenges:
  - understanding and increasing the voltage
  - covering the entire solar spectrum: IR & tandem cells
  - stability
- Low-cost manufacturing

Photovoltaics: ... just taking off



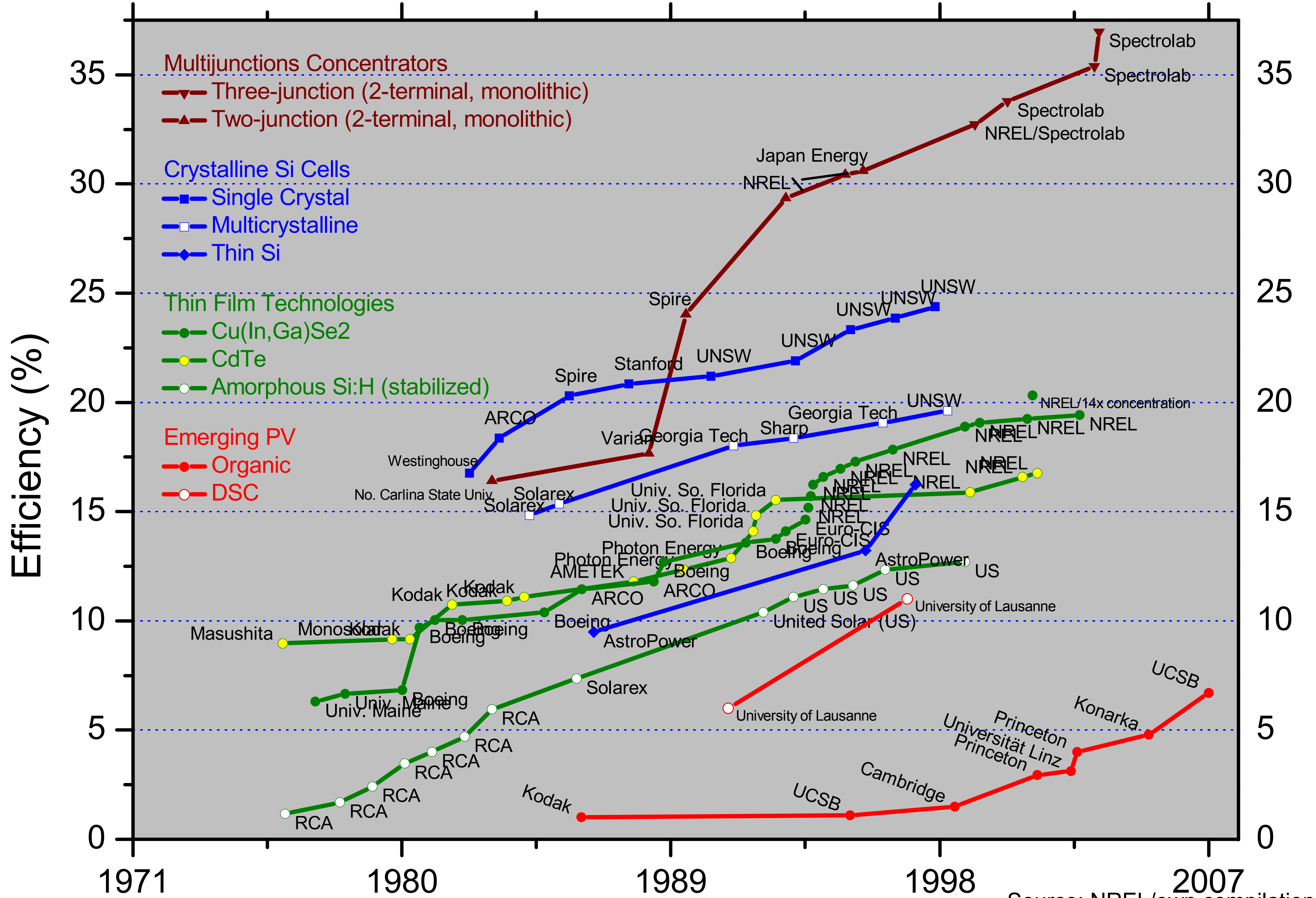
[1] assuming 1.4% increase per year (source: IEA WEO 2004, "World Alternative Policy Scenario") and starting at 17.400 TWh world electricity production in 2004 (source: BMWi "Zahlen und Fakten - Energiedaten", 2006)

[2] assuming average of 1200 kWh yearly electricity production per installed kWp module power (own estimate)

[3] TWh = Terrawatt-hour = 1 billion Kilowatt-hours

PV „power generation " market will grow by another factor of 5000!

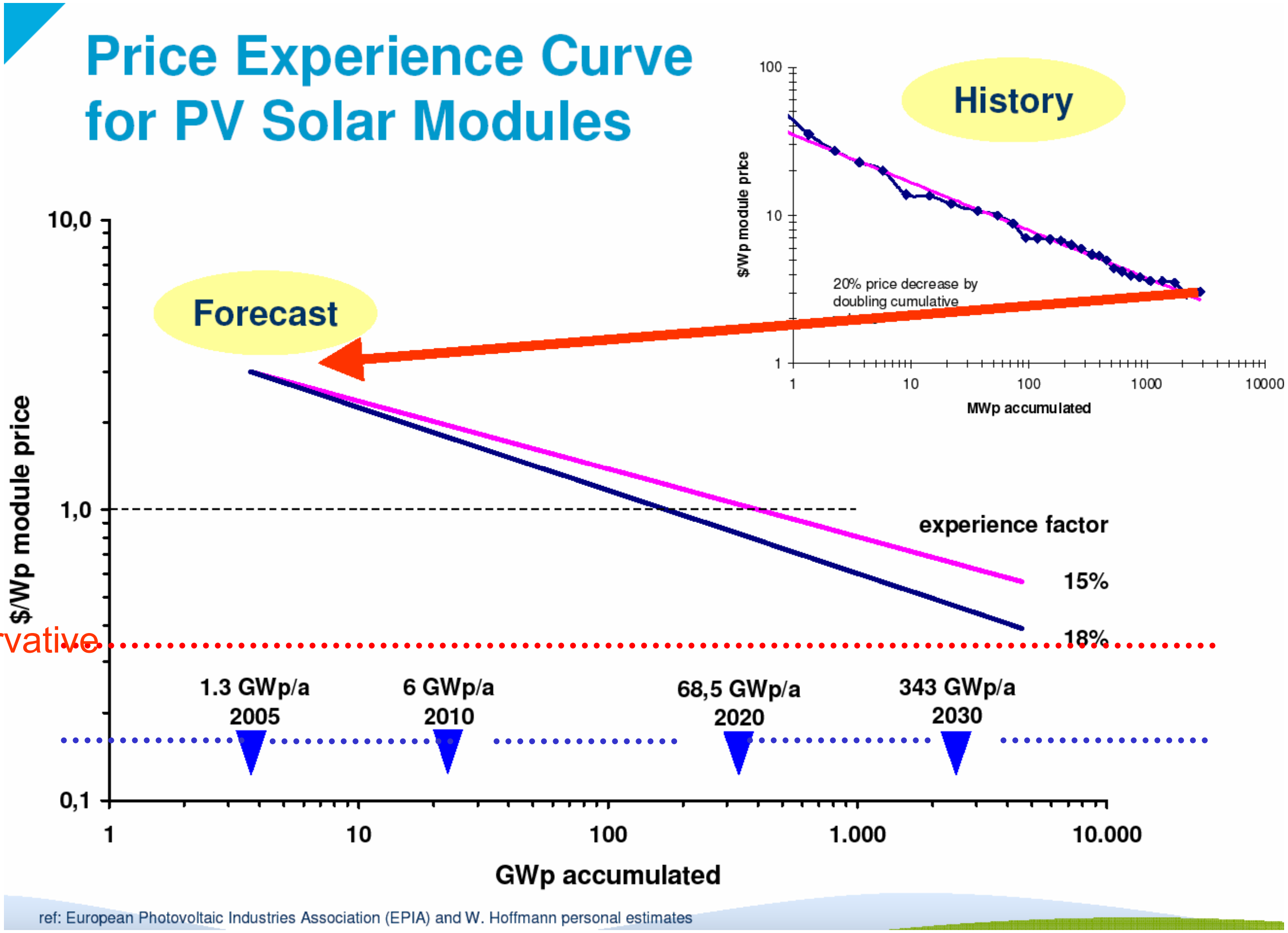
Status: Efficiencies



Source: NREL/own compilation

Cost of organic solar cells

- Factor of 2-3 below Si/thin film seems possible
- What is needed: 8-10% in module = 13-15% in lab
- Lifetime at least 10 years

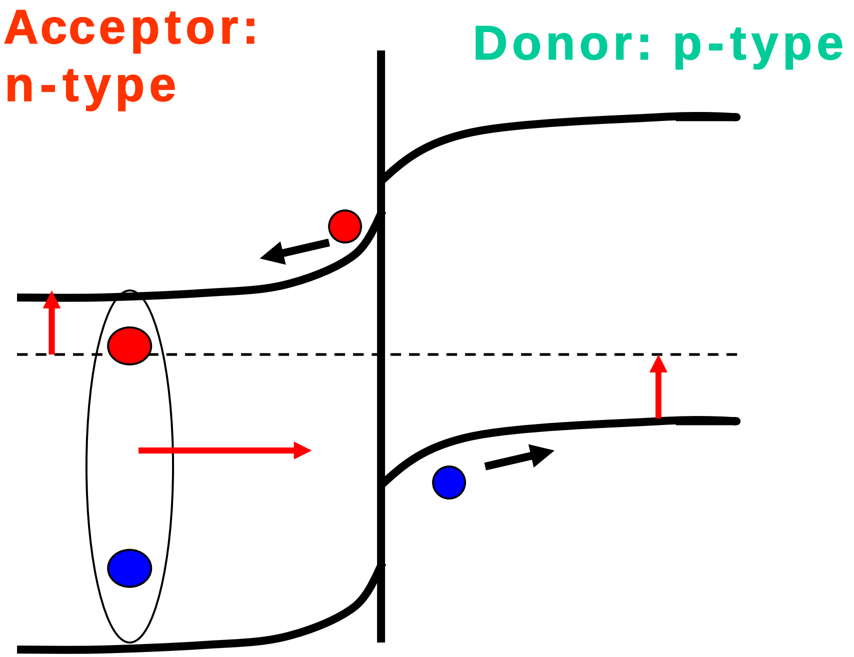


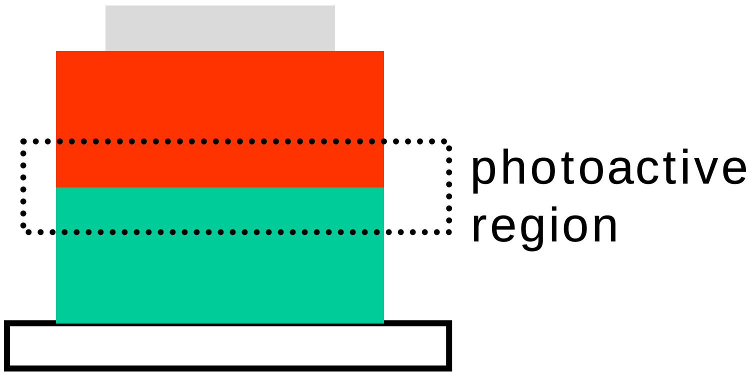
ref: European Photovoltaic Industries Association (EPIA) and W. Hoffmann personal estimates

Status of small molecule organic solar cells

- Started in 1986 with Ching Tang‘s work at Kodak
- Looked for Solar Cell and also stumbled into OLED
- Big progress, but still immature compared to OLED
- Many contributions I cannot cover: Yase, Saito, Fostiropoulos, Schlettwein, Lemmer, Kowalsky, ….

Small molecule organic solar cells





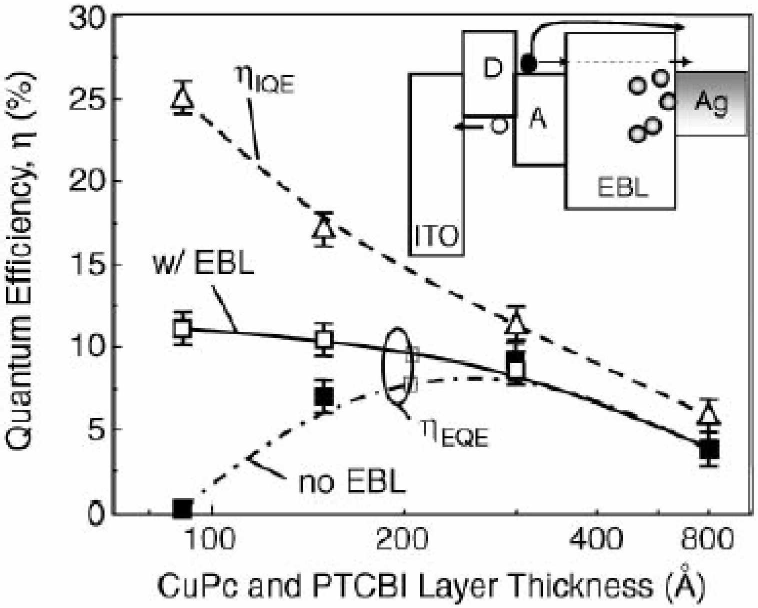
C.W. Tang (Kodak) (1986)

- Materials: CuPc/PTCBI
- efficiency 1%
- exciton diffusion length too low

=> active layer very thin

Exciton blocker layer

- P. Peumans, V. Bulovic, and S.R. Forrest, Appl. Phys. Lett. 76 (2000 2650
- Excitons are reflected
- Optical standing wave is optimized



pin-Structure

- M. Hiramoto et al., J. Appl. Phys. 72 (1992) 3781
- Pin-structure, but no active Fermi level control in p- and n-layer
- Bulk heterojunction!

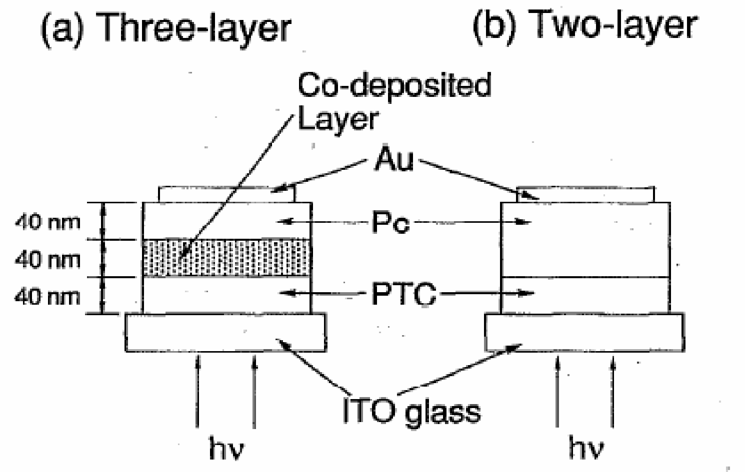
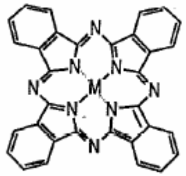


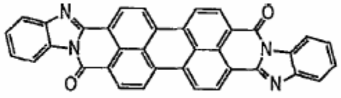
FIG. 2. Schematic representation of the configurations of (a) three-layered and (b) two-layered organic solar cells.

3782 J. Appl. Phys., Vol. 72, No. 8, 15 October 1992

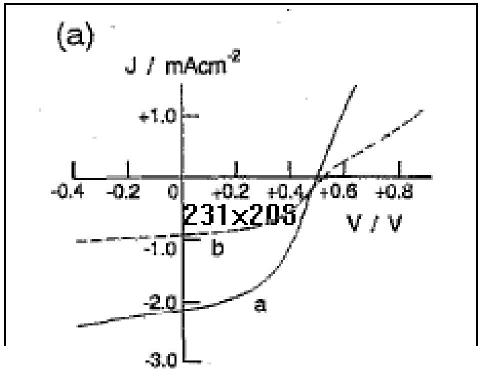


Pc (M=H_2,Cu)

Me-PTC



Im-PTC

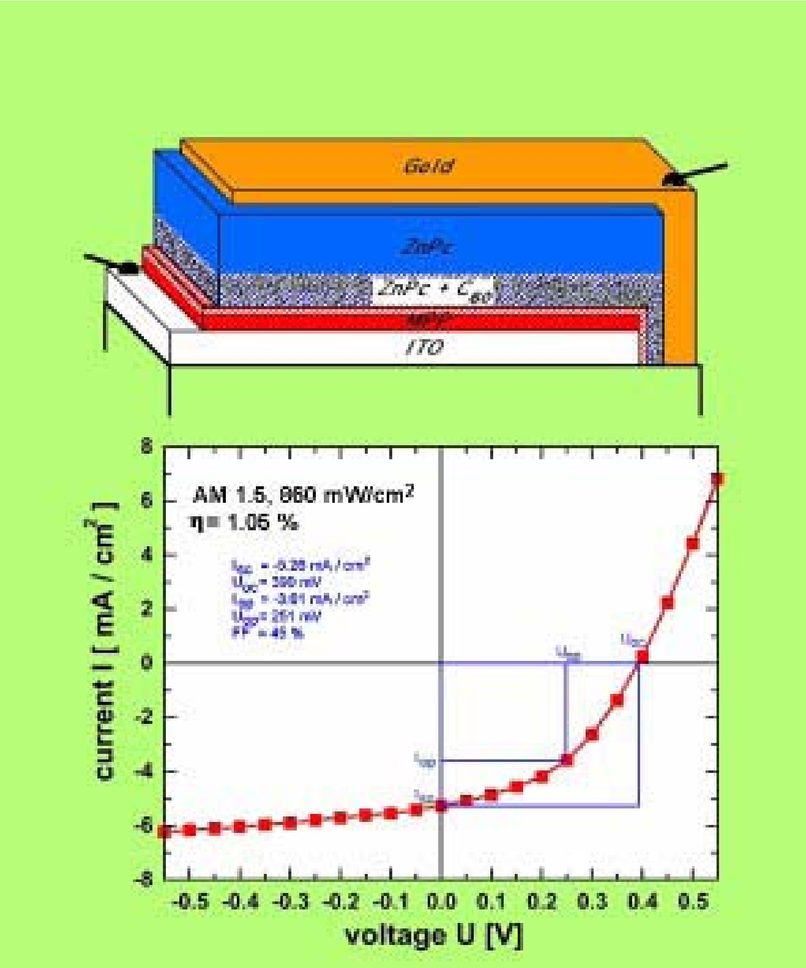


Bulk heterojunction with C_{60}

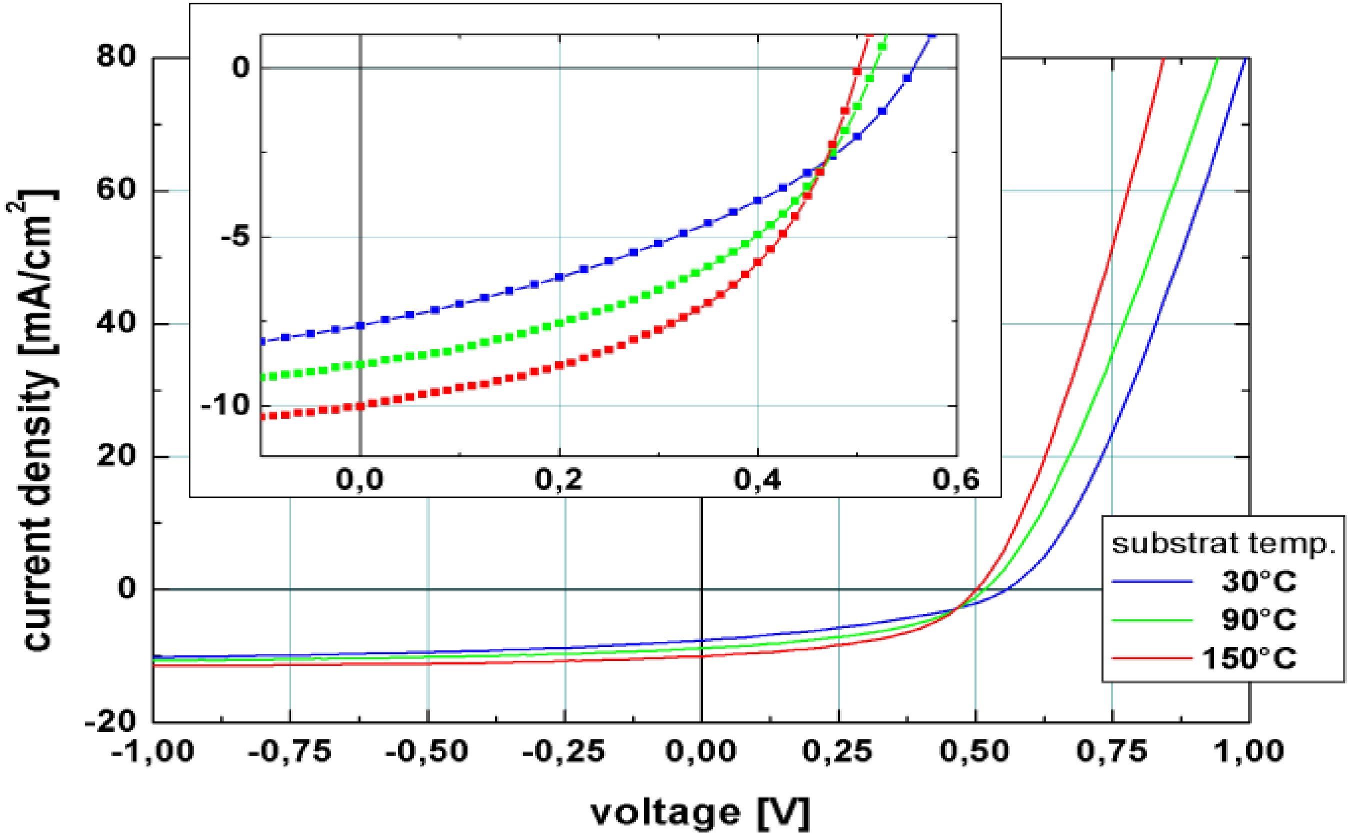
- D. Meissner et al.
  Photon **2** (1999), 34 – 37

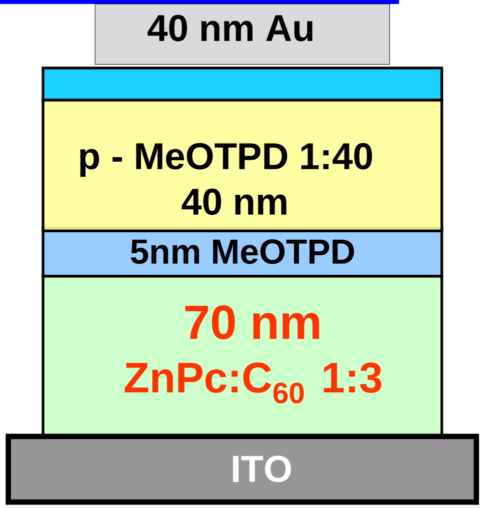
- Prepared by coevaporation

- Problem: morphology control



Influence of blend layer morphology





40 nm Au

p - MeOTPD 1:40
40 nm

5nm MeOTPD

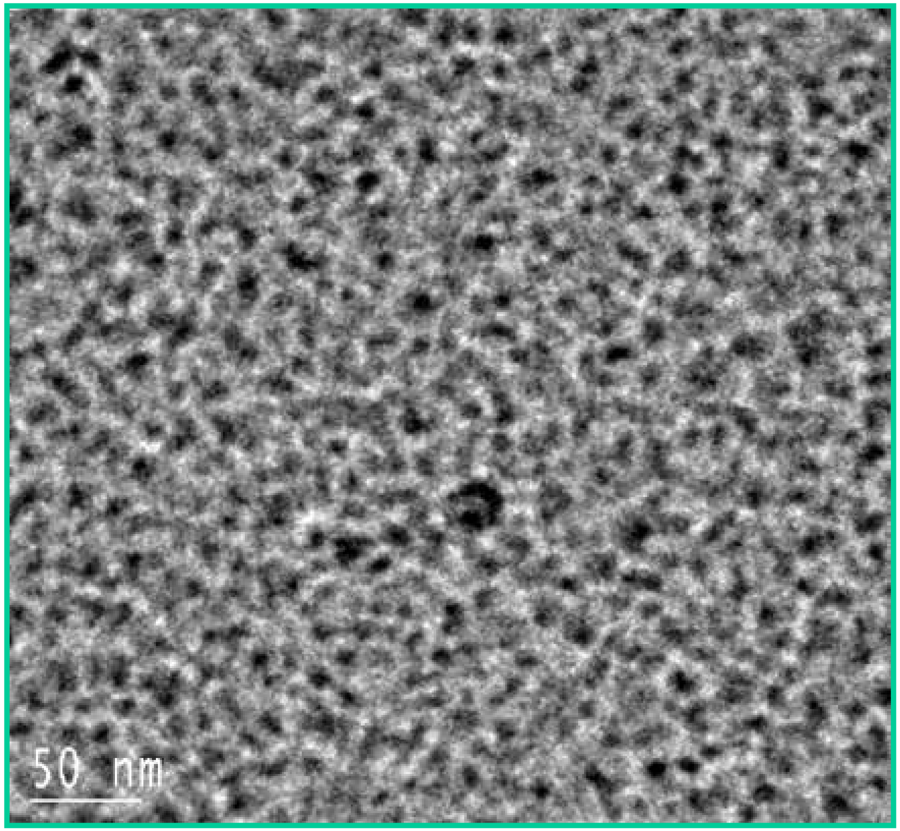
70 nm
ZnPc:C_{60} 1:3

ITO

temp	I_{SC} [mA]	U_{OC} [V]	FF [%]	eff [%]	reverse slope [mA/cm²V]
30°C	7,63	0,56	37,6	1,61	2,4
90°C	8,79	0,52	44,9	2,05	1,7
150°C	10,03	0,50	49,0	2,44	1,3

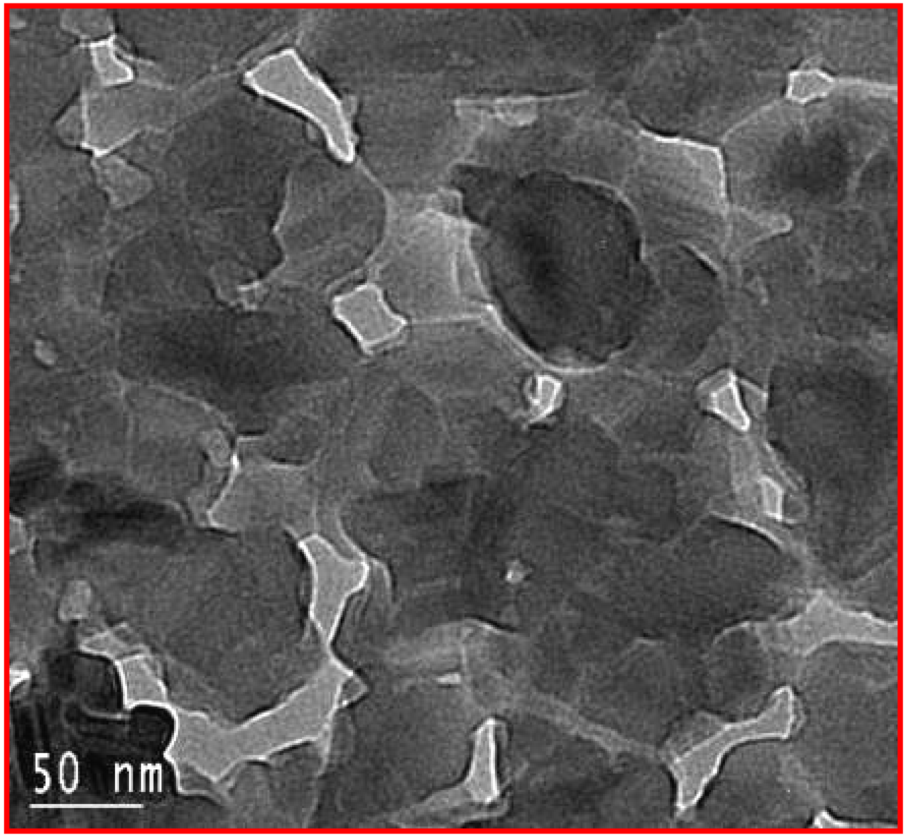
Substrate temperature ⇔ blend layer morphology
REM pictures for ZnPc*C_{60}

30°C



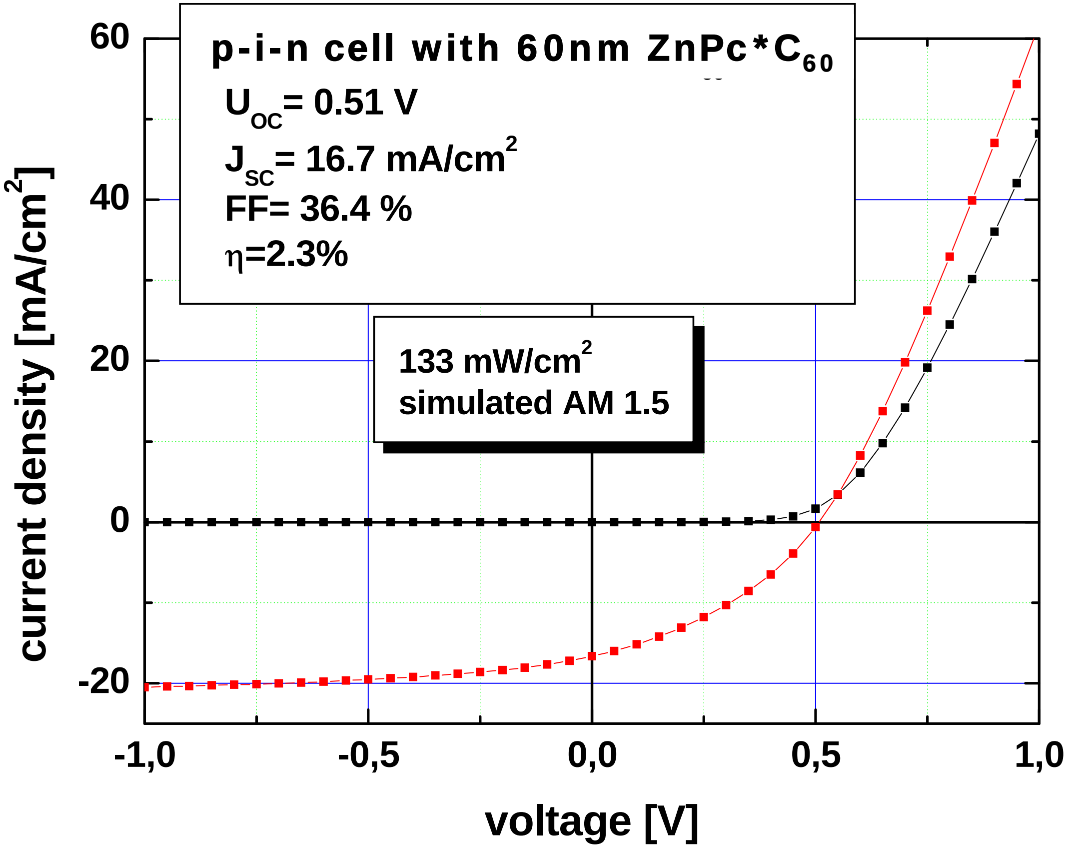
- no domains
- amorphous structure

150°C



- domains of 20-100nm
- 120° angles => hexagonal structure of C_{60} nanocrystallites

ZnPc-C_{60}-BH cells: the benchmark



- Current status: η≈3.5% (Hiramoto, Forrest, IAPP)
- Clearly behind polymer solar cells
- Limits: insufficient absorption; low mobility in blend; high voltage loss

Unpublished data (Hiramoto): 1µm absorber!, η≈5% with ultrapure C_{60}

Tandem cells

- M. Hiramoto et al., Chem. Lett. **1990** (1990) 327
- First efficient realization: A. Yakimov & S.R. Forrest, Appl. Phys. Lett. **80** (2002) 1667
- Au Clusters recombination centers

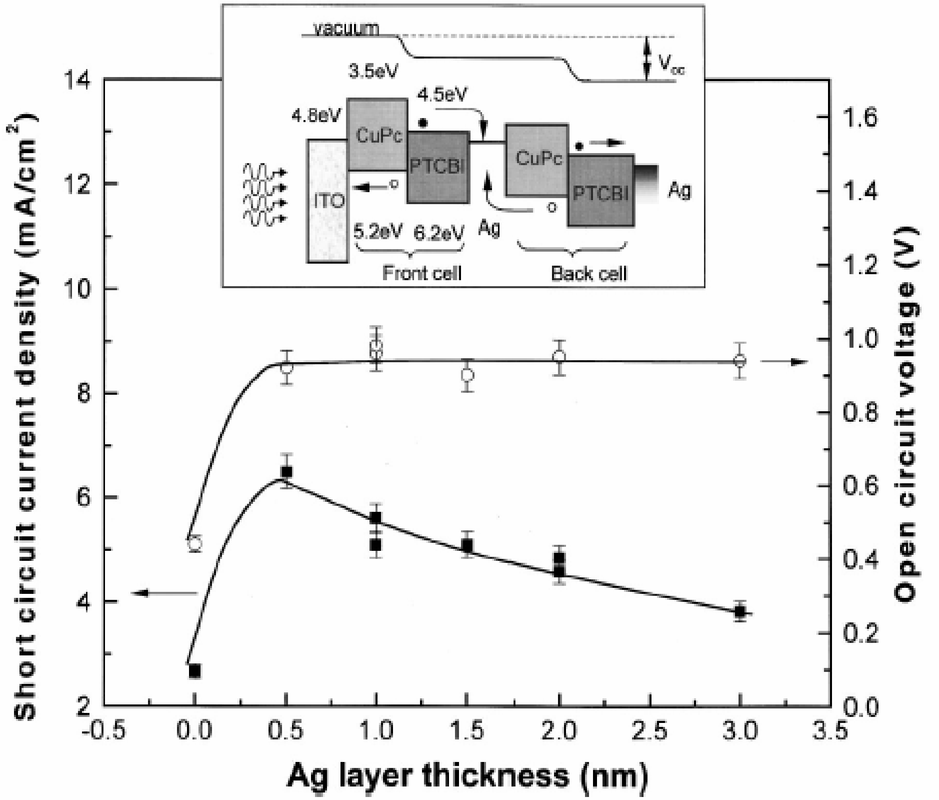


FIG. 1. Short circuit current density (closed squares, left axis) and open circuit voltage (open circles, right axis) for dual cells having Ag interlayers of different average thicknesses. The measurements were performed under AM 1.5, 100 mW/cm^2 (1 sun) illumination. The inset shows the proposed energy level diagram of the dual-HJ device.

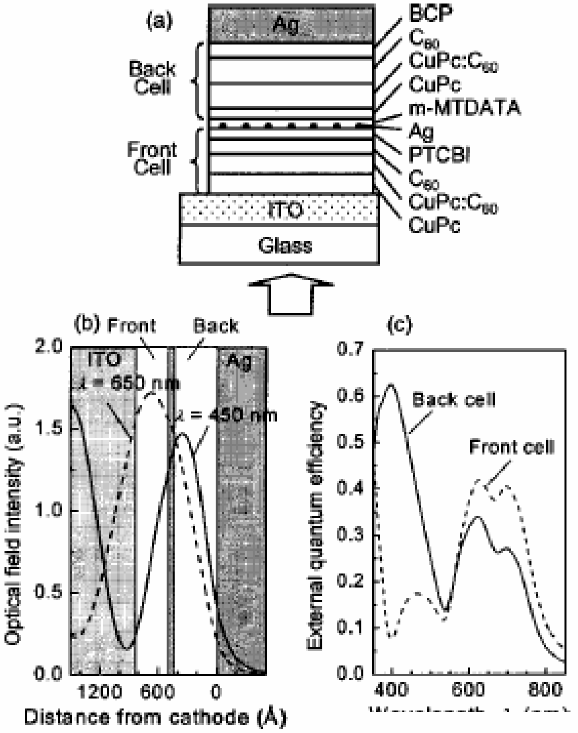
Best literature value for small-molecule cell

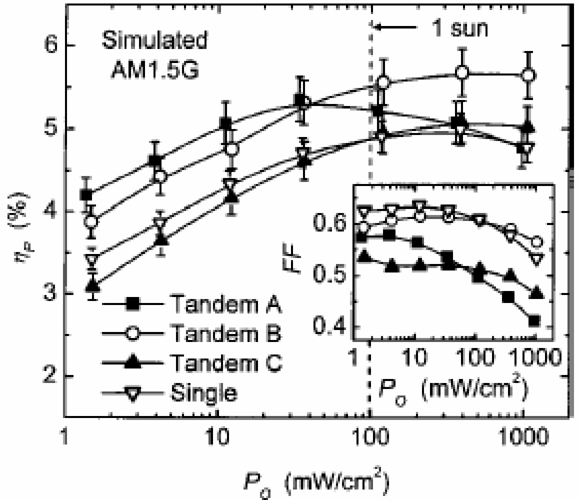
- J. Xue et al. Appl. Phys. Lett. 85 (2004) 5757

- CuPc/C60:CuPc/PTCDI tandem cell

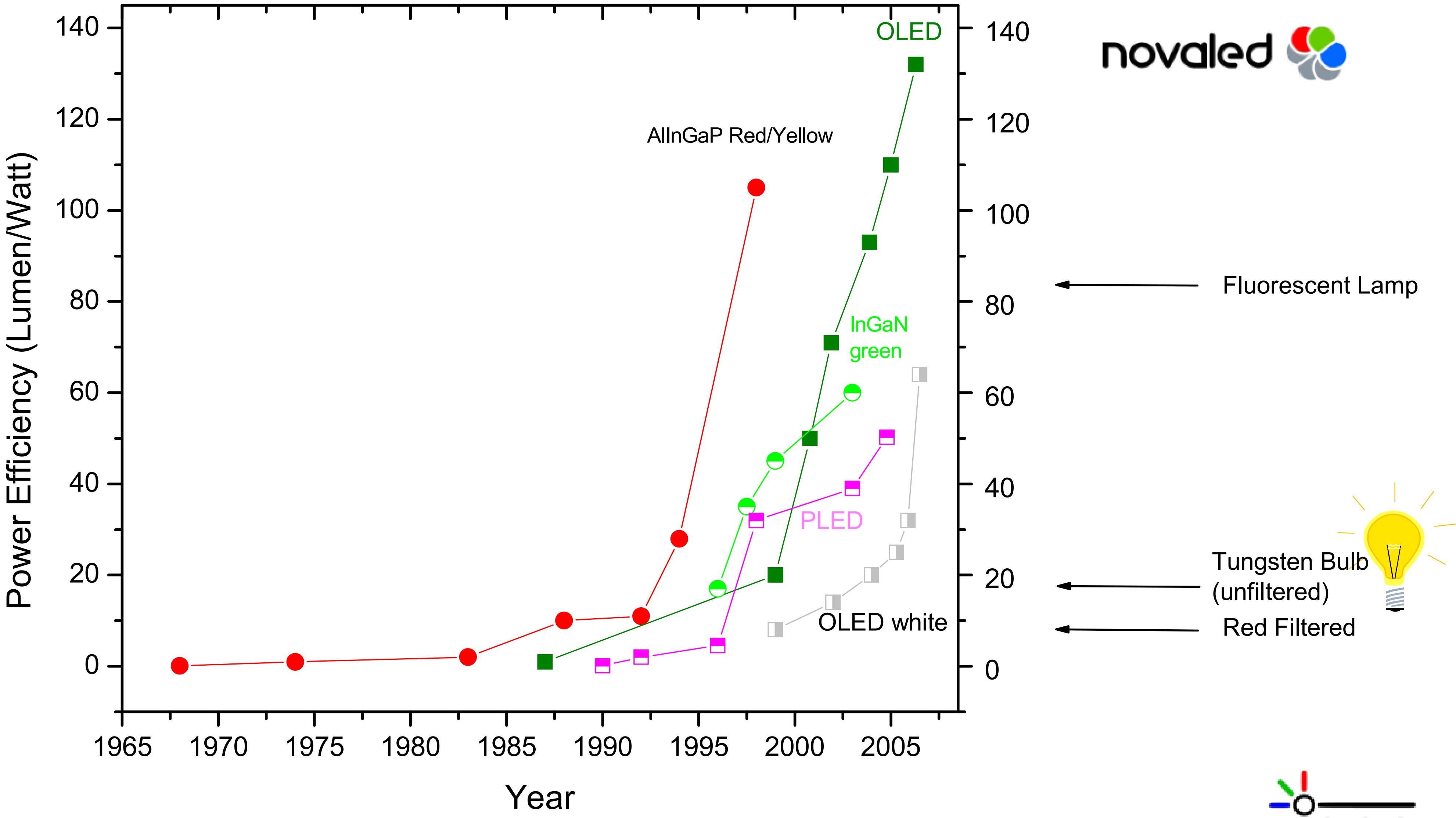
- Au Clusters and p-doped interlayer

- 5.7% at 1 sun





OLED: Polymer is behind small molecule



Why are polymer solar cells better than small-molecule solar cells?

- Bulk heterojunction morphology control: many more “handles” for polymers:
  - solvent
  - temperature
  - concentration

- Polymer might have a basic mobility advantage in bulk heterojunction

- Materials basis broader

Outline

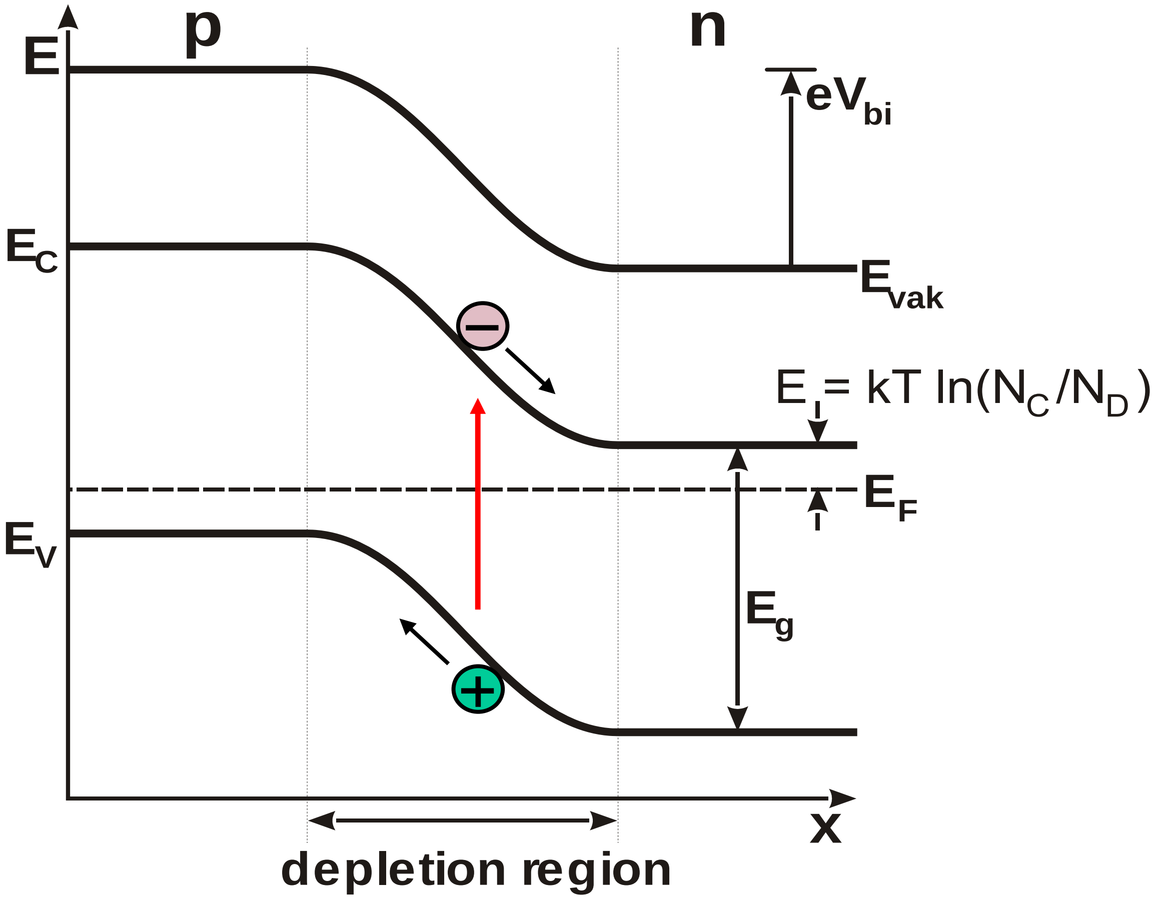
- Some thoughts about Organic PV in general

- Status of small-molecule organic solar cells:
  key innovations in the past

- Future challenges:
  - understanding and increasing the voltage
  - covering the entire solar spectrum: tandem cells
  - stability

- Low-cost manufacturing

Origin of the open-circuit voltage



- Inorganic solar cell: Built-in voltage by Fermi-level difference of doped transport layers

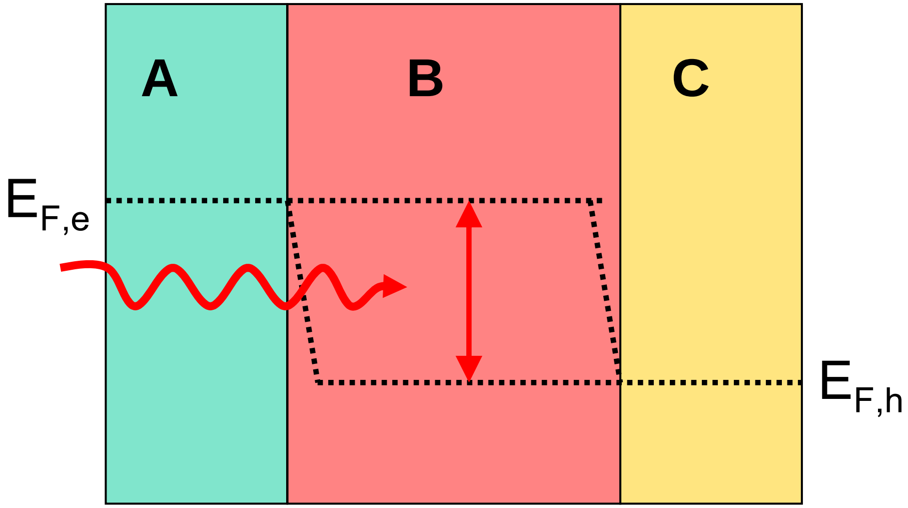
$$\boxed{eV_{bi} = E_g - kT\ln[N_C \cdot N_V / N_D \cdot N_A]}$$

- Organic solar cells: built-in voltage by contacts?

Open-circuit voltage cannot excedeed V_{bi} !

The Würfel picture

Ideal solar cell structure to reach maximum V_{OC}:



- Photoactive material **B** between highly conductive non-absorbing materials **A** and **C**

- interfaces **A/B** and **B/C** perfectly semipermeable membranes: only one type of carrier can pass

-> V_{OC} is independent from V_{bi}
-> V_{OC} equals splitting of quasi-Fermi levels

Peter Wuerfel, *Physics of solar cells: from principles to new concepts.* Weinheim, Wiley-VCH (2005).

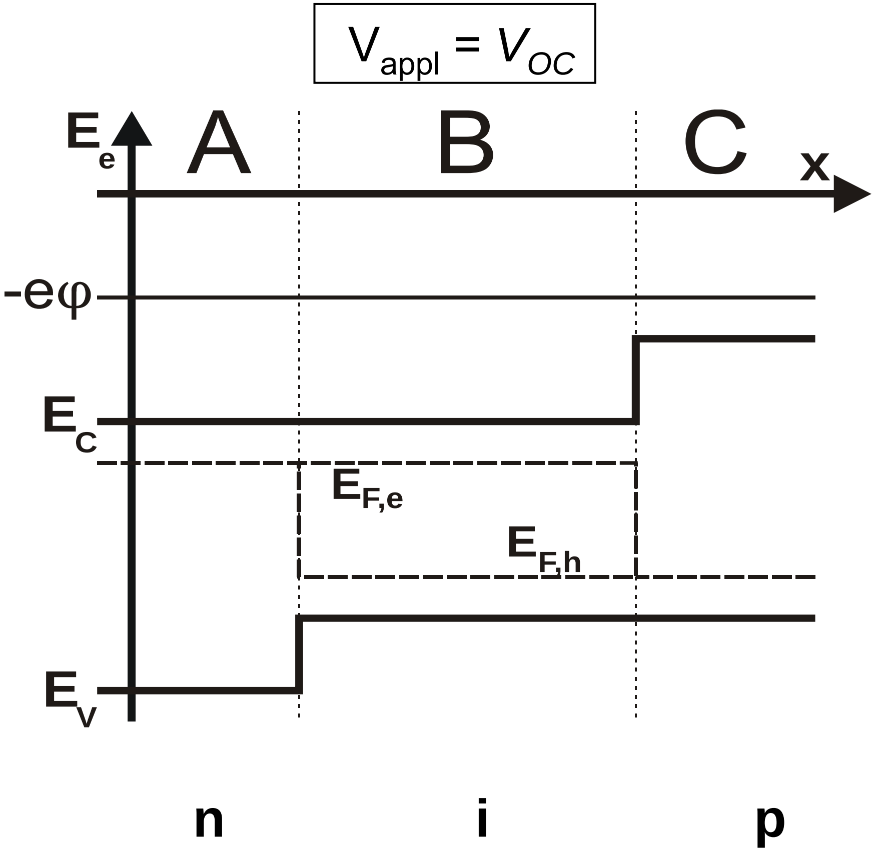
The Würfel picture realized in an organic solar cell

- Window materials with suitable hetero-offset work as selective membranes

- Carriers driven by drift **and** diffusion

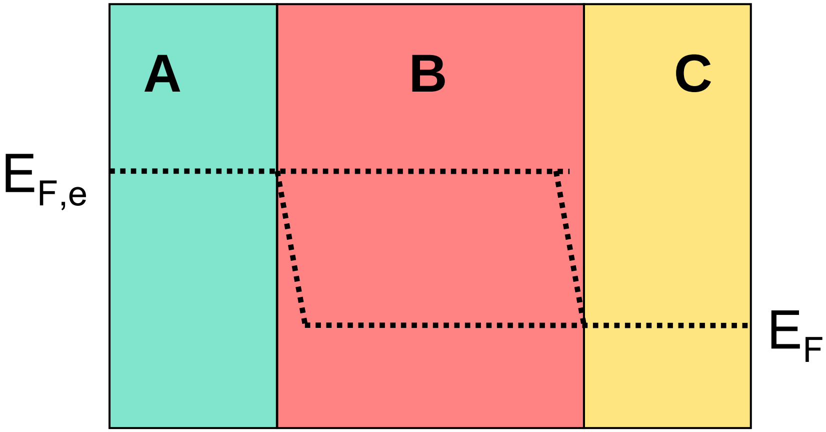
$$J(x) = \frac{\sigma_n}{e}\,\mathrm{grad}\,E_{F,n} + \frac{\sigma_p}{e}\,\mathrm{grad}\,E_{F,p}$$

- Quasi-Fermi levels need to be „picked up“ by transport materials:
  $E_{F,e}$ in A needs to be high,
  $E_{F,h}$ in C needs to be low:
  pin-structure with doped layers



$$V_{OC} \leq \mathrm{E}_{\mathrm{F,n}} - \mathrm{E}_{\mathrm{F,h}} = \mathrm{E}_{\mathrm{g}} - kT \cdot \ln \frac{N_C N_V}{n_n n_p}$$

The 3 steps to high voltage according to the Würfel picture



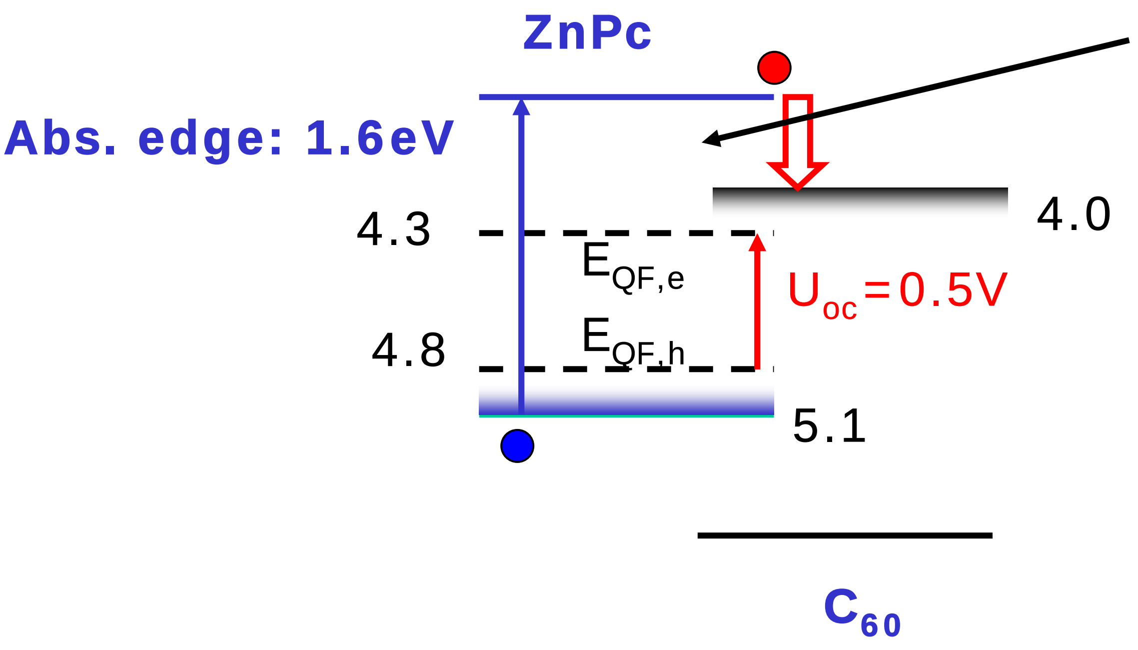
1. Quasi-Fermi-levels $E_{F,e}$ and $E_{F,h}$ must be well separated in absorber ⇒ excitons must be efficiently separated in absorber with little energy loss

2. Quasi-Fermi-levels must be „picked up“ well by transport layers A and C

3. Energy loss at electrodes must be avoided

Step 1: Optimize the exciton separation, but with little energy loss

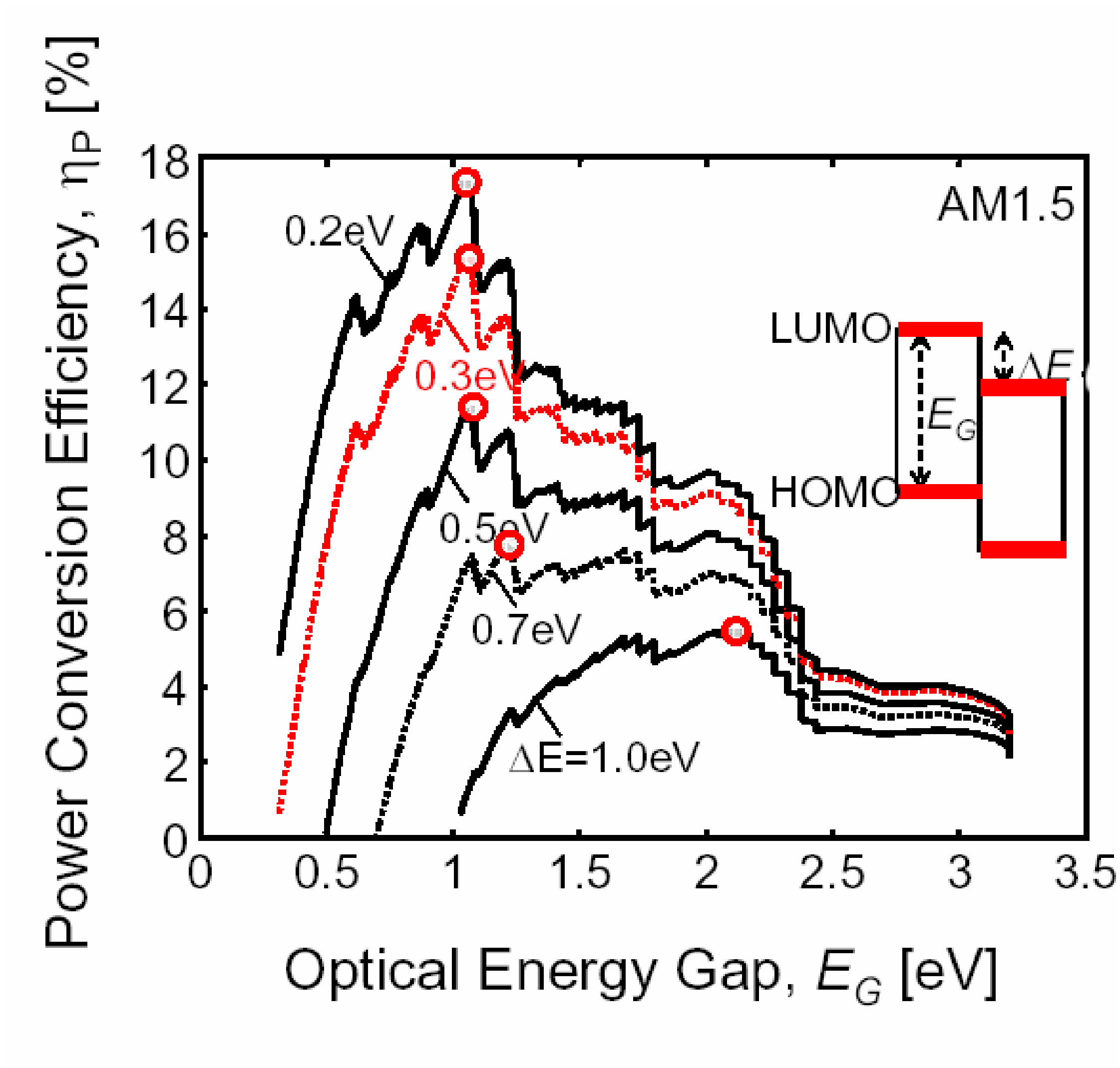
Example system: ZnPc/C_{60}



Minimum energy loss
upon charge separation:
0.2….0.7 eV?

(recent Results in polymers:
Durrant et al., JACS, in press)

Efficiency Outlook: Peumans data



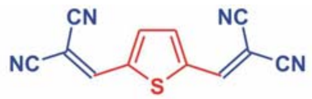
- Low-offset is critical, in particular for low gap
- Optimum gap around 1eV
- Efficiencies ≈ 10% feasible: tandem concepts needed!

Source: P. Peumans

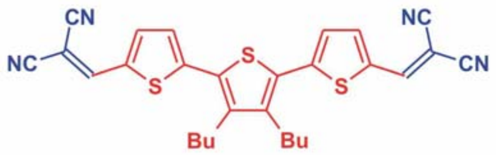
New low gap thiophene oligomers

University of Ulm
Department Organic
Chemistry II

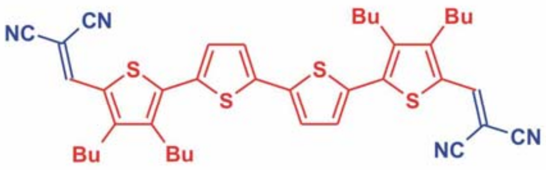
E.Brier,
E. Reinold,
P. Kilickiran,
P. Bäuerle



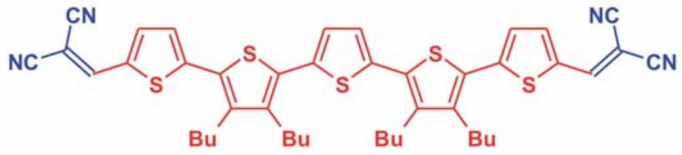
DCV1T



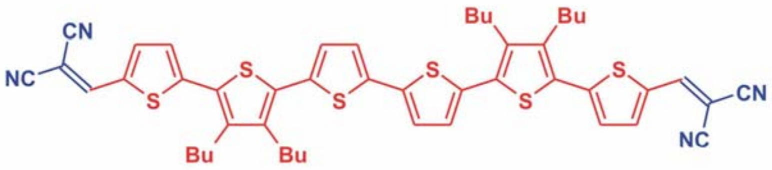
DCV3T



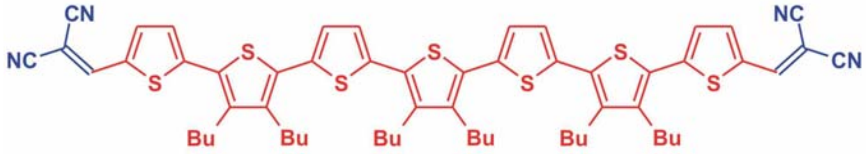
DCV4T



DCV5T

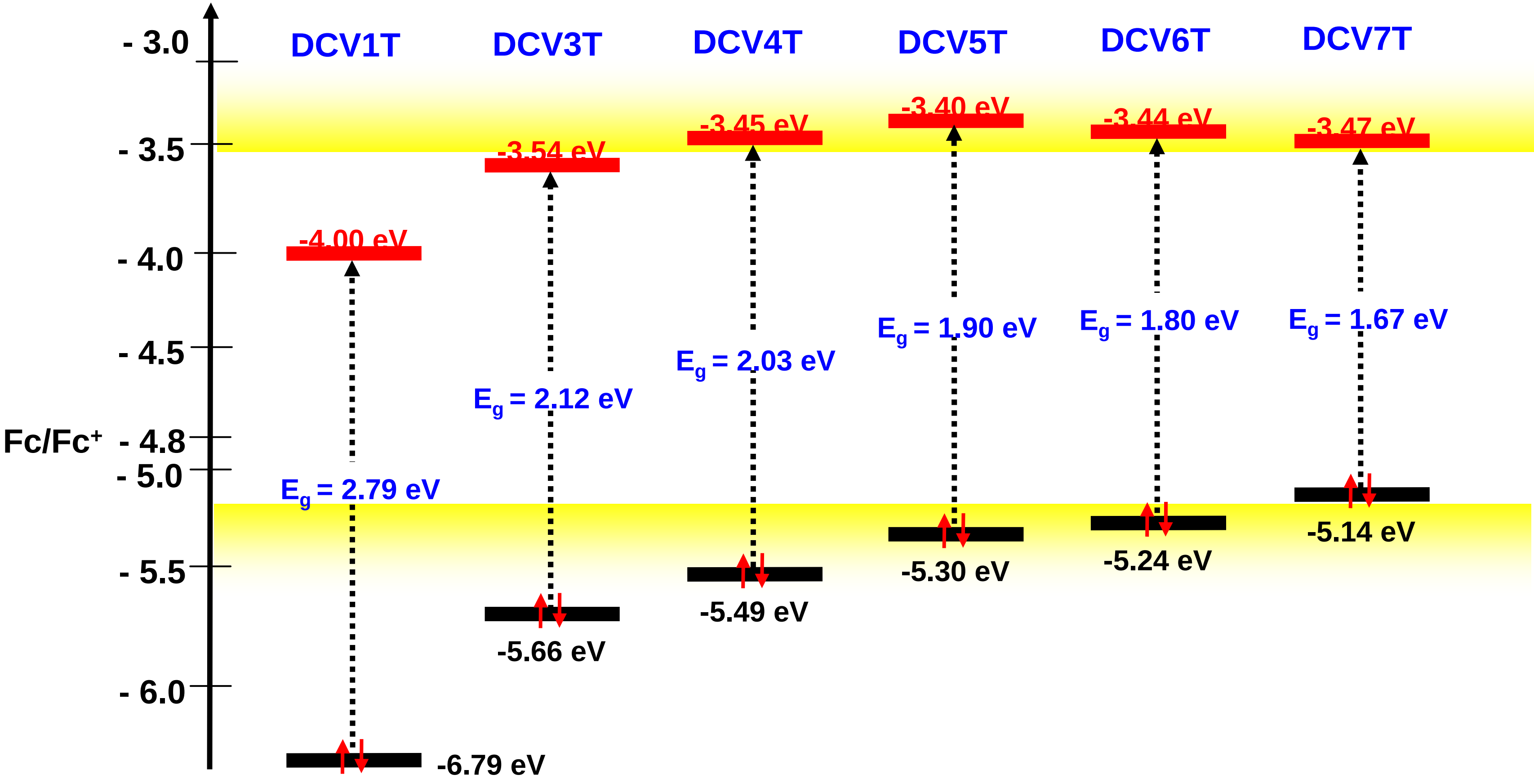


DCV6T

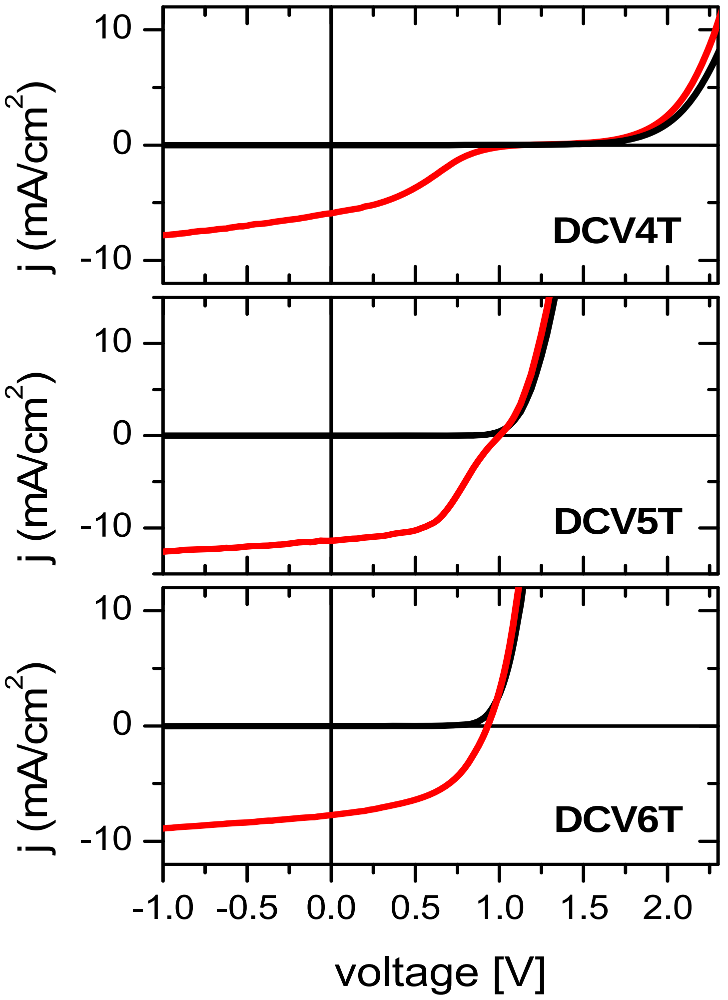


DCV7T

New low gap thiophene oligomers: energy gaps



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***

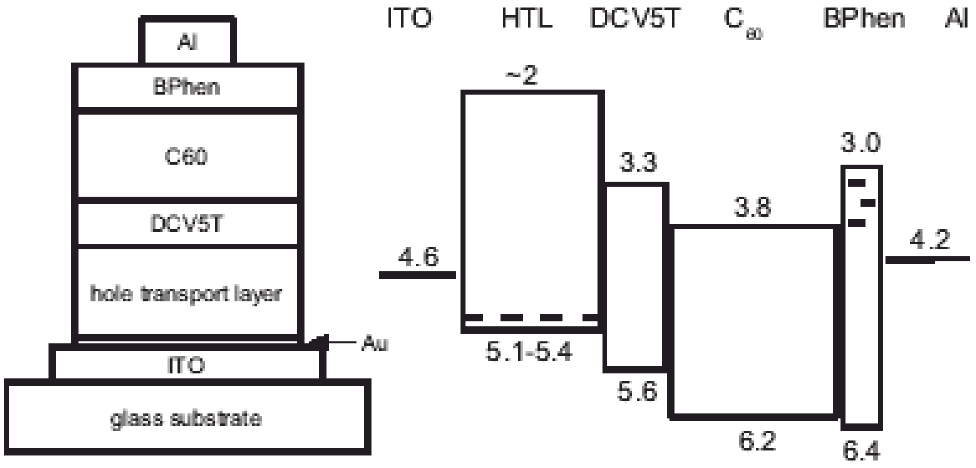
with **increasing** chain length

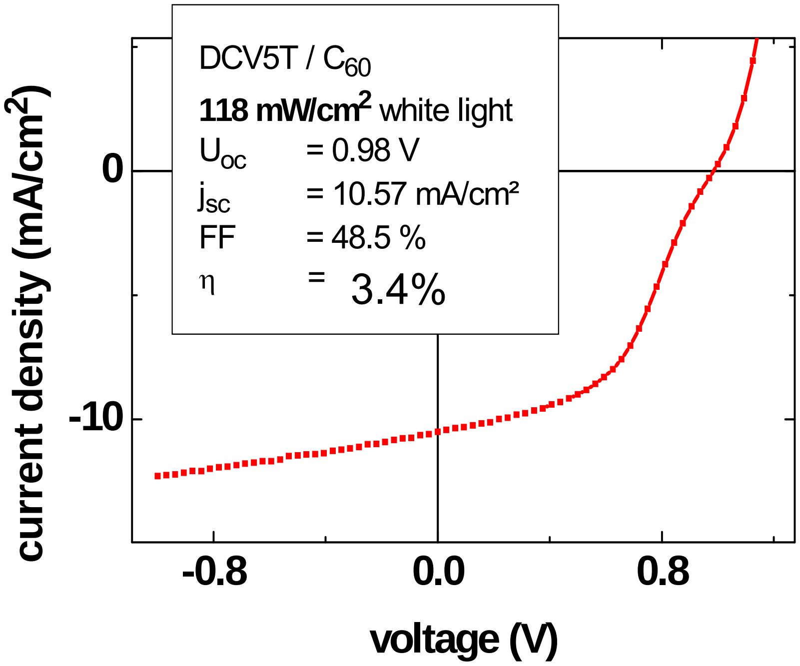
ITO / Au(1) / pTNATA(30) / pNPD(10,4:1) / NPD(5) / **DCVnT** (8) / **C_{60}** (40) / Bphen(6) / Al(100)

for PCE calculation, a spectral mismatch of 0.7 has to be taken into account.

Cells based on DCV5T / C_{60} flat heterojunction

- V_{oc} up to 1V for material with optical gap 1.77eV
- Single cell with up to ~ 4% efficiency @ 7nm active layer

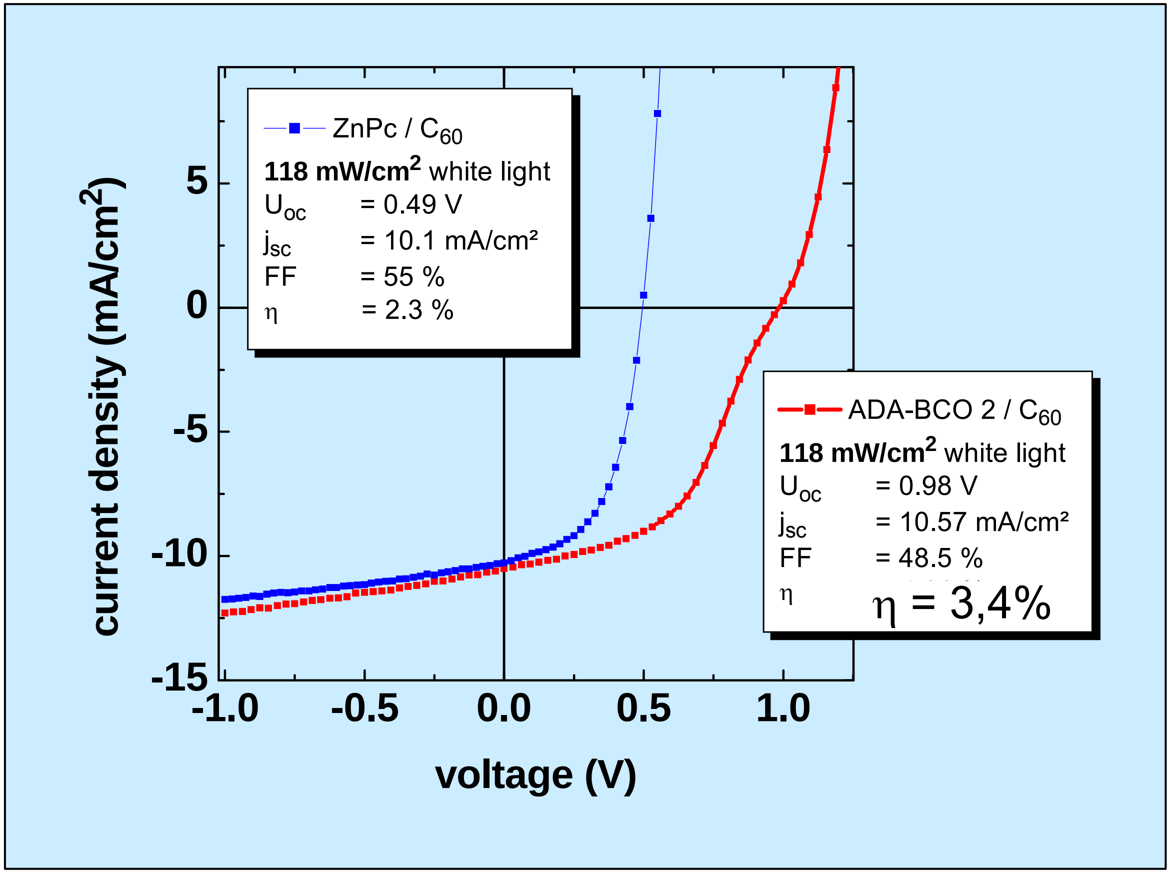




Thicker absorber layers: low fill factor -> transport problem

K. Schulze et al., Adv. Mat. **18**, 2872 (2006)

Comparison DCV5T vs. ZnPc



ZnPc / C_{60}

118 mW/cm^2 white light

U_{oc} = 0.49 V

j_{sc} = 10.1 mA/cm²

FF = 55 %

η = 2.3 %

ADA-BCO 2 / C_{60}

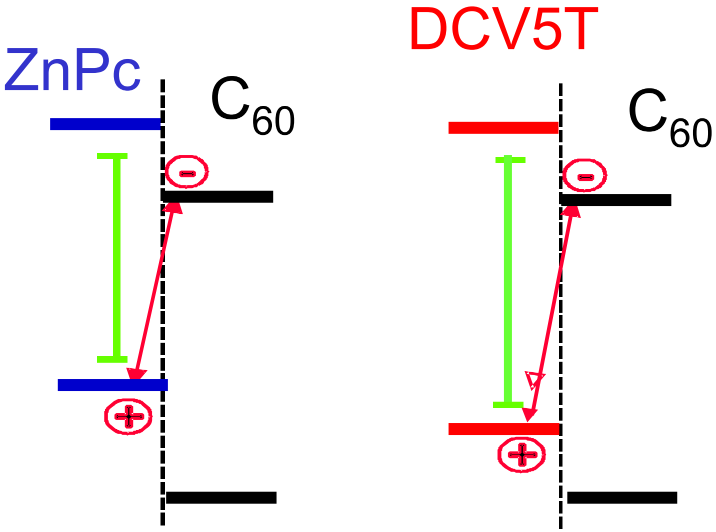
118 mW/cm^2 white light

U_{oc} = 0.98 V

j_{sc} = 10.57 mA/cm²

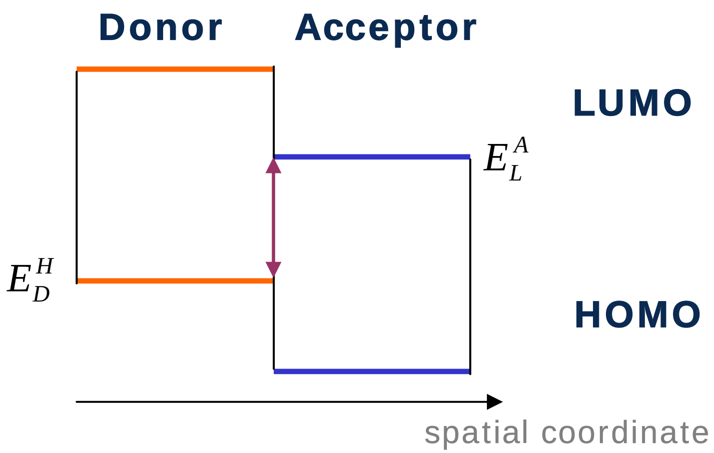
FF = 48.5 %

η = 3,4%



Study of Exciton Separation

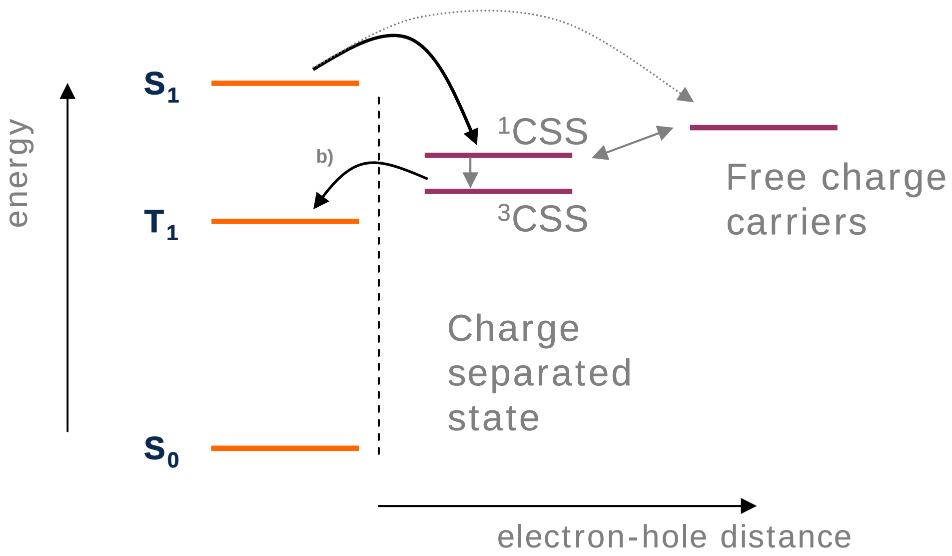
R. Schueppel et al., ChemPhysChem 8, 1497-1503 (2007)



High open circuit voltage:

$$eV_{oc} \propto E_L^A - E_H^D$$

Increasing energetic gap between
LUMO of acceptor and HOMO of donor



Impact on charge separation:

- minimized loss of free energy
- dissociation of geminate pair necessary, excess energie of „hot exciton“ is minimized
- recombination into the triplet state becomes possible

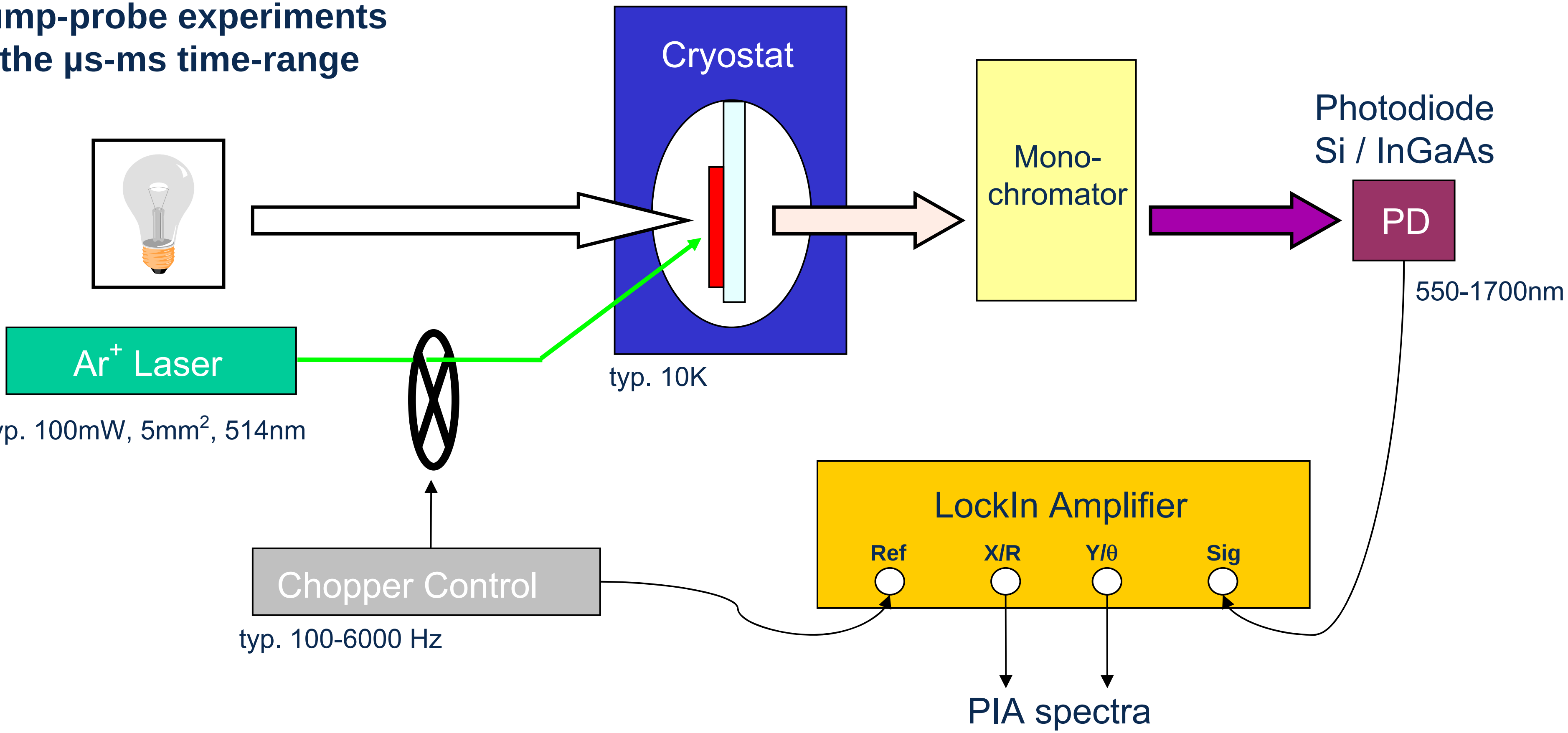
=> introducing a loss mechanism

Veldman *et al.*, Thin Film Solids 511, 333 (2006)

[b] pathway suggested by Ford *et al.*, PRB 71, 125212 (2005)

Photoinduced Absorption Spectroscopy

Pump-probe experiments in the µs-ms time-range



Cryostat

typ. 10K

Mono-
chromator

Photodiode
Si / InGaAs

PD

550-1700nm

Ar$^+$ Laser

typ. 100mW, 5mm^2, 514nm

Chopper Control

typ. 100-6000 Hz

LockIn Amplifier

Ref **X/R** **Y/θ** **Sig**

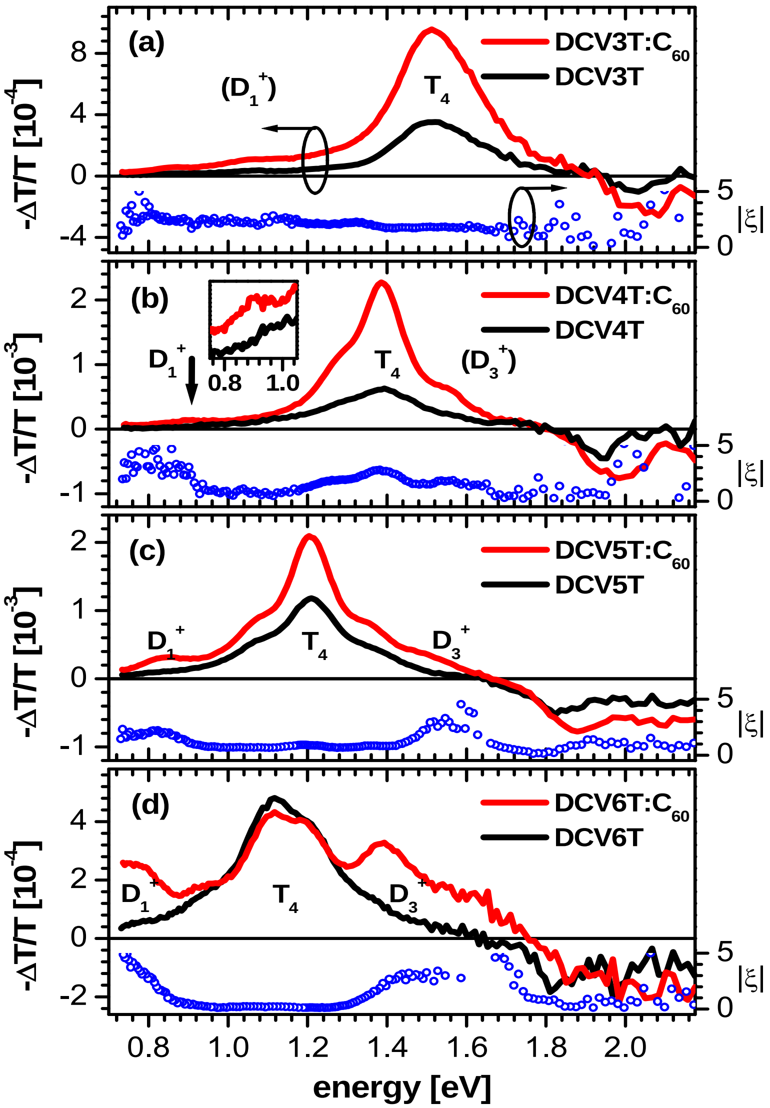
PIA spectra

Parameters in photoinduced absorption experiment:

wavelength, modulation frequency, temperature, pump intensity, bias voltage

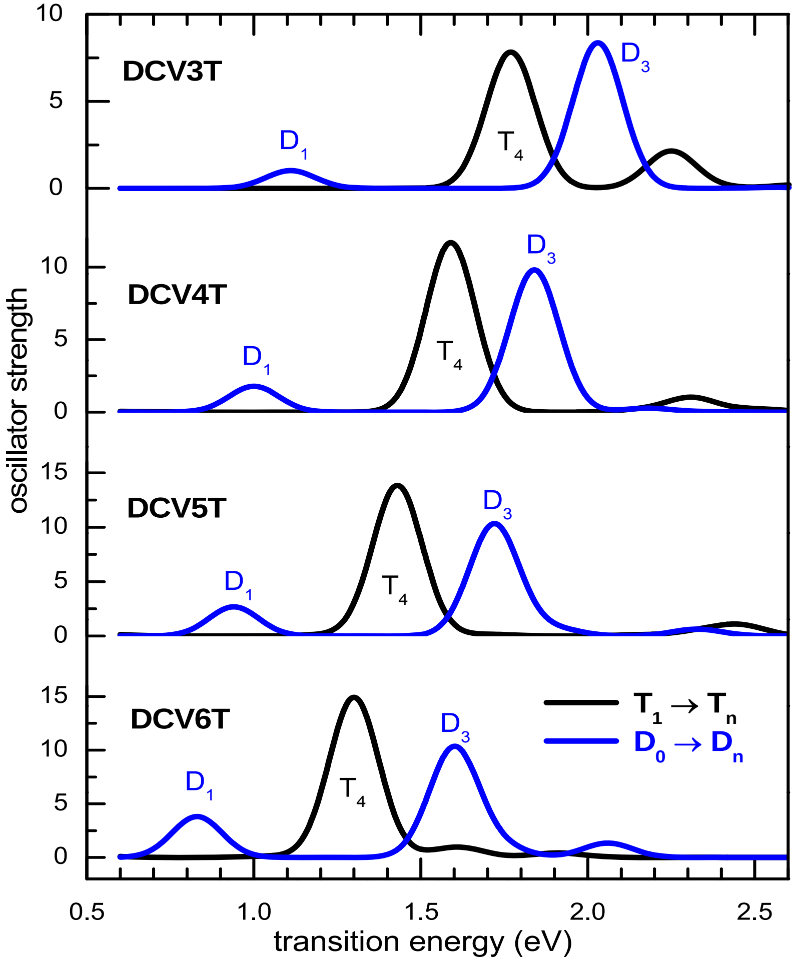
Photoinduced Absorption Spectroscopy: Results

PIA spectra of DCVnT:C60 at 10K

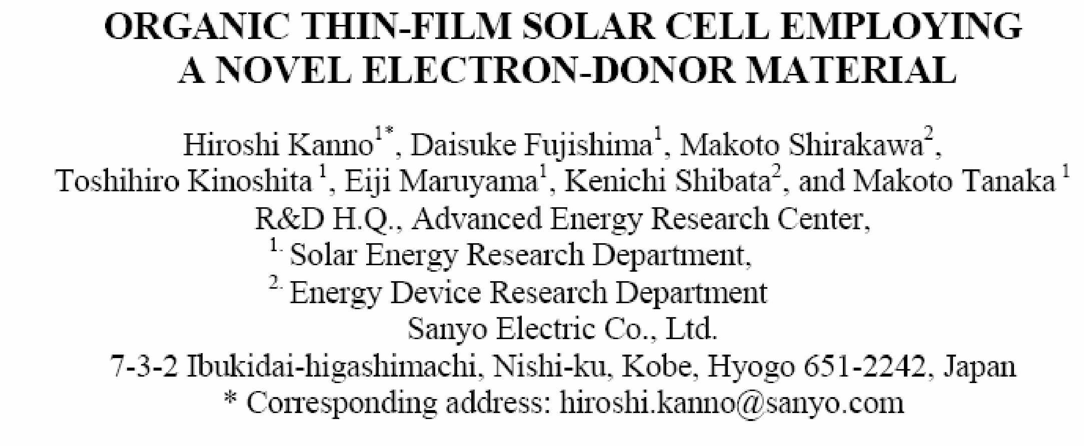


ξ: Normalized difference of neat and blend layer PIA spectra

Triplet ($T_1 \rightarrow T_n$) and cation ($D_0 \rightarrow D_n$) transitions of DCVnT; TD-DFT calculations by Karin Schmidt (B3LYP, unrestricted, relaxed geometries)



Another new Donor Material



ORGANIC THIN-FILM SOLAR CELL EMPLOYING A NOVEL ELECTRON-DONOR MATERIAL

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Toshihiro Kinoshita[1], Eiji Maruyama[1], Kenichi Shibata[2], and Makoto Tanaka[1]
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- V_{OC} of 0.92V
- Efficiency: 3.56%

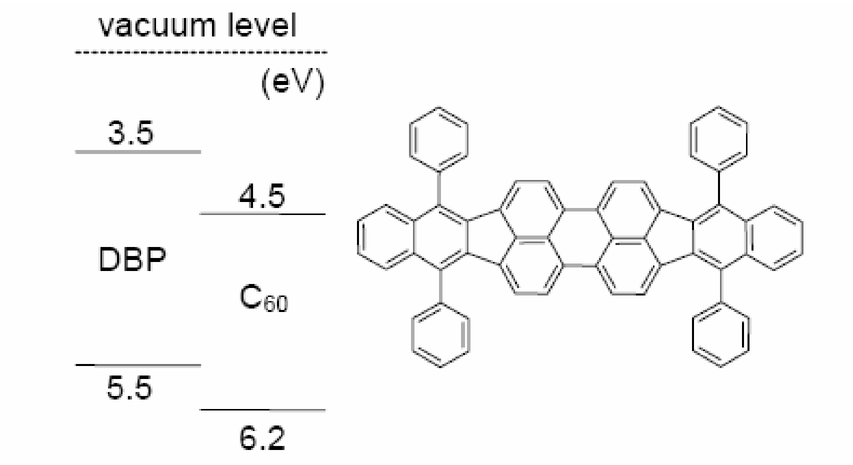
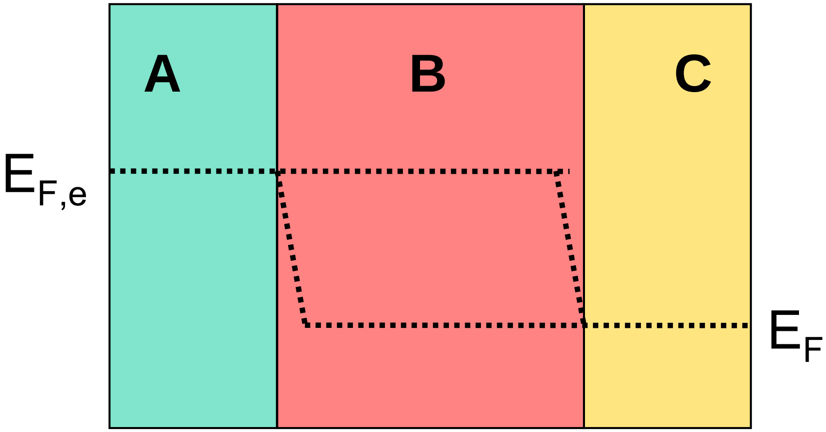


Fig. 1 Left: The proposed energy diagram of DBP and C_{60}. Right: The molecular structure of DBP

The 3 steps to high voltage according to the Würfel picture

1. Quasi-Fermi-levels $E_{F,e}$ and $E_{F,h}$ must be well separated in absorber
   $\Rightarrow$ excitons must be efficiently separated in absorber with little energy loss

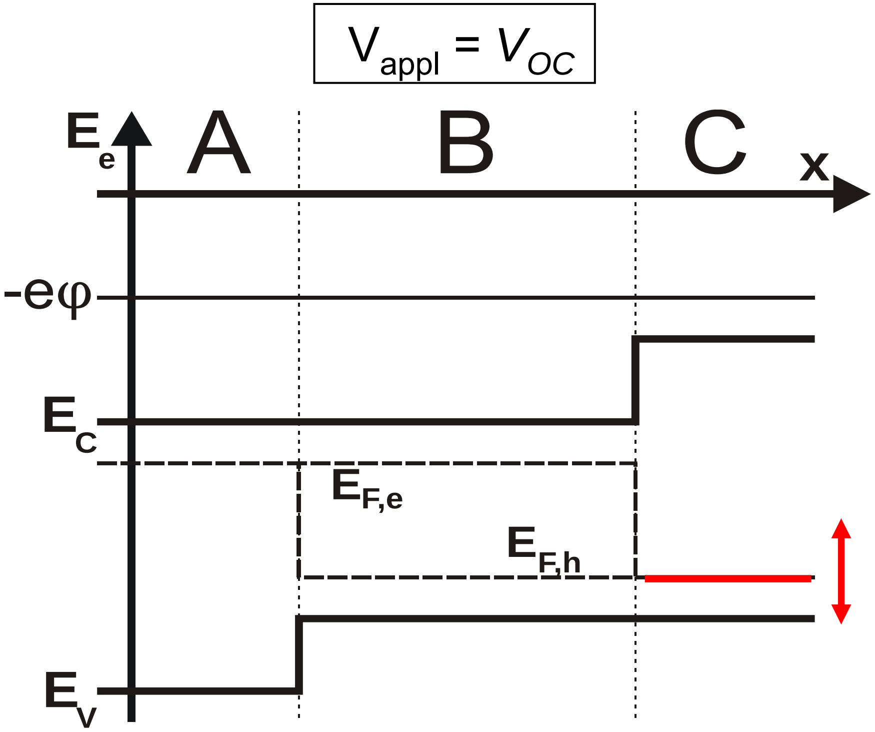


2. Quasi-Fermi-levels must be „picked up“ well by transport layers A and C

3. Energy loss at contact to electrodes must be avoided

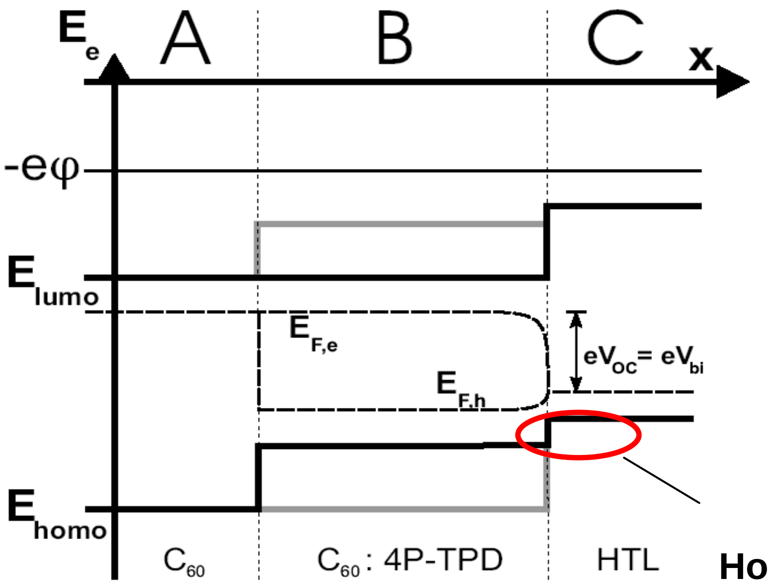
Systematic study of quasi-Fermi level „pick-up“

- C. Uhrich et al., Adv. Functional Materials **17**, 2991 (2007)
- Shift of the Fermi level in the hole transport layer C
- Comparison of flat and bulk heterojunction



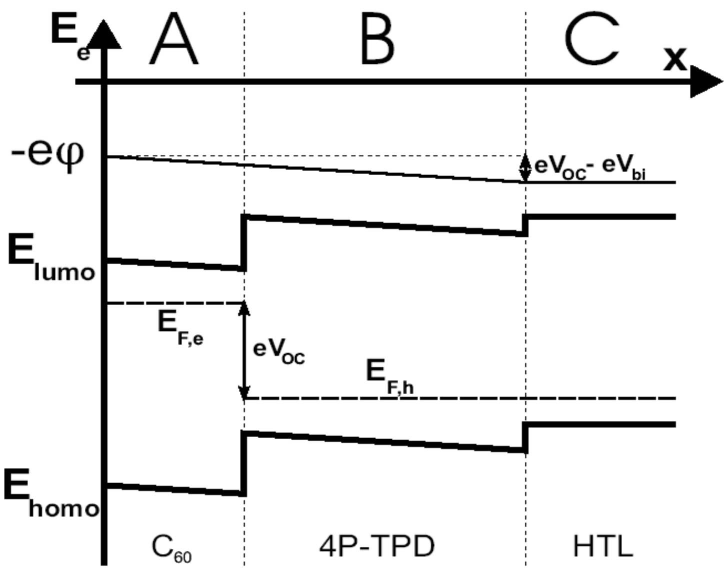
Comparison bulk vs. planar heterojunction

Potential curves under open circuit condition:



Hole accumulation

bulk heterojunction



planar heterojunction

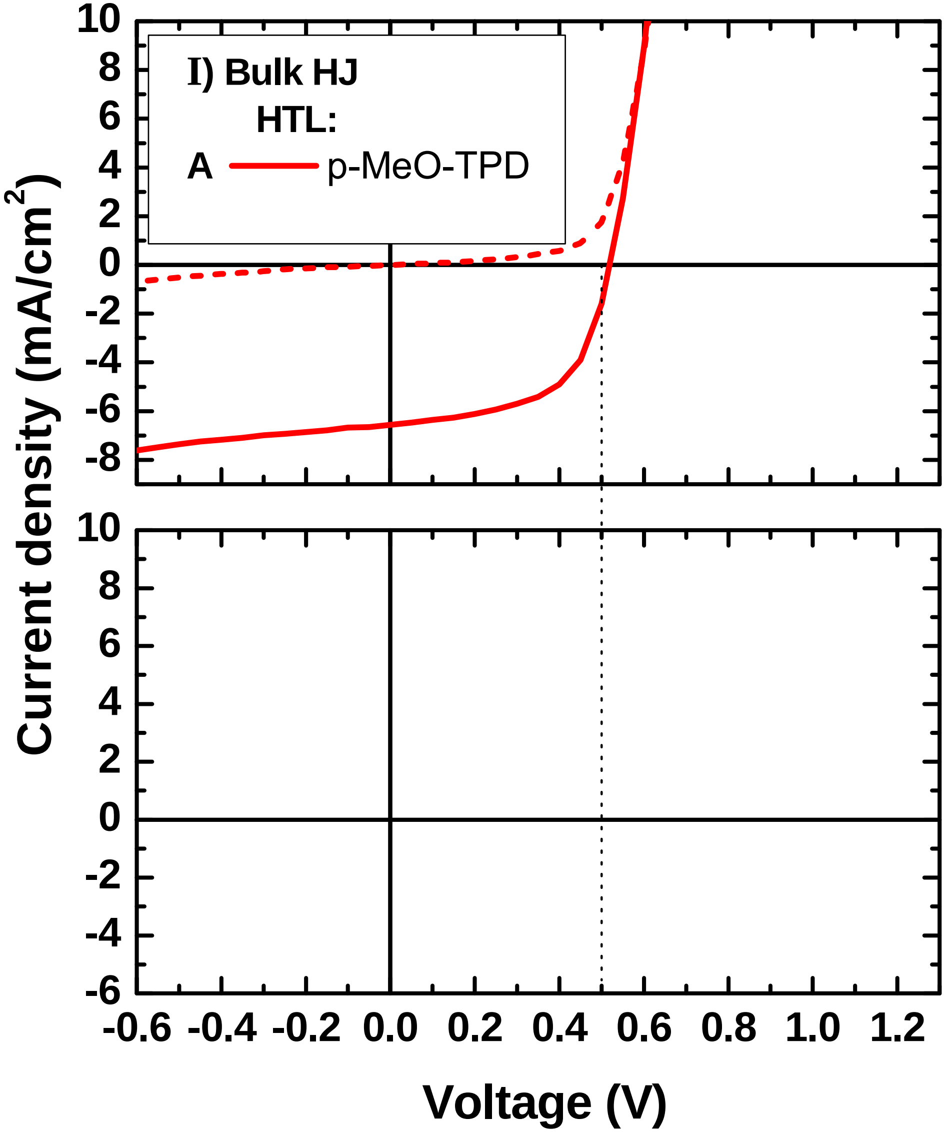
- charge carrier generation in **B**
- HOMO offset betw. 4P-TPD and HTL: enhanced recombination at **B/C**

-> V_{OC} cannot exceed V_{bi} significantly

- charge carrier generation at interface **A/B**
- C_{60} and HTL are spatially separated
- quasi-Fermi levels are constant
- charge carriers are driven against electric field by diffusion ($V_{OC} > V_{appl} > V_{bi}$)

-> V_{OC} equals splitting of QFL and exceeds V_{bi}

Influence of hole transporter Fermi level on V_{oc}

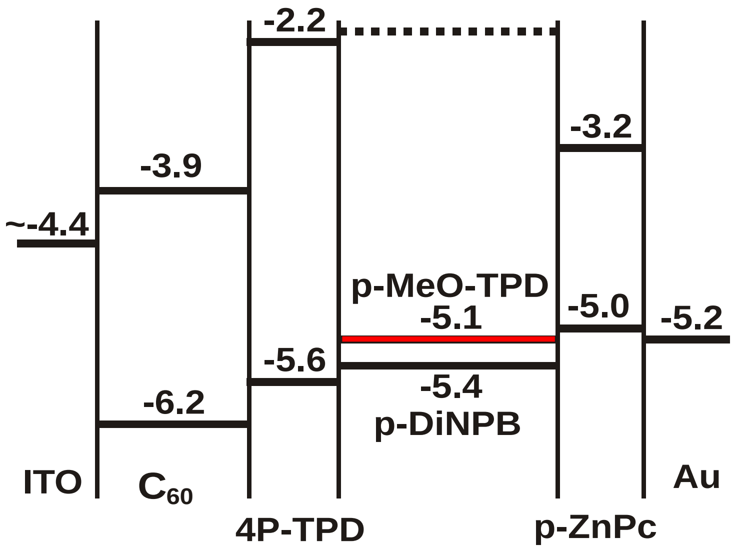


I) bulk HJ

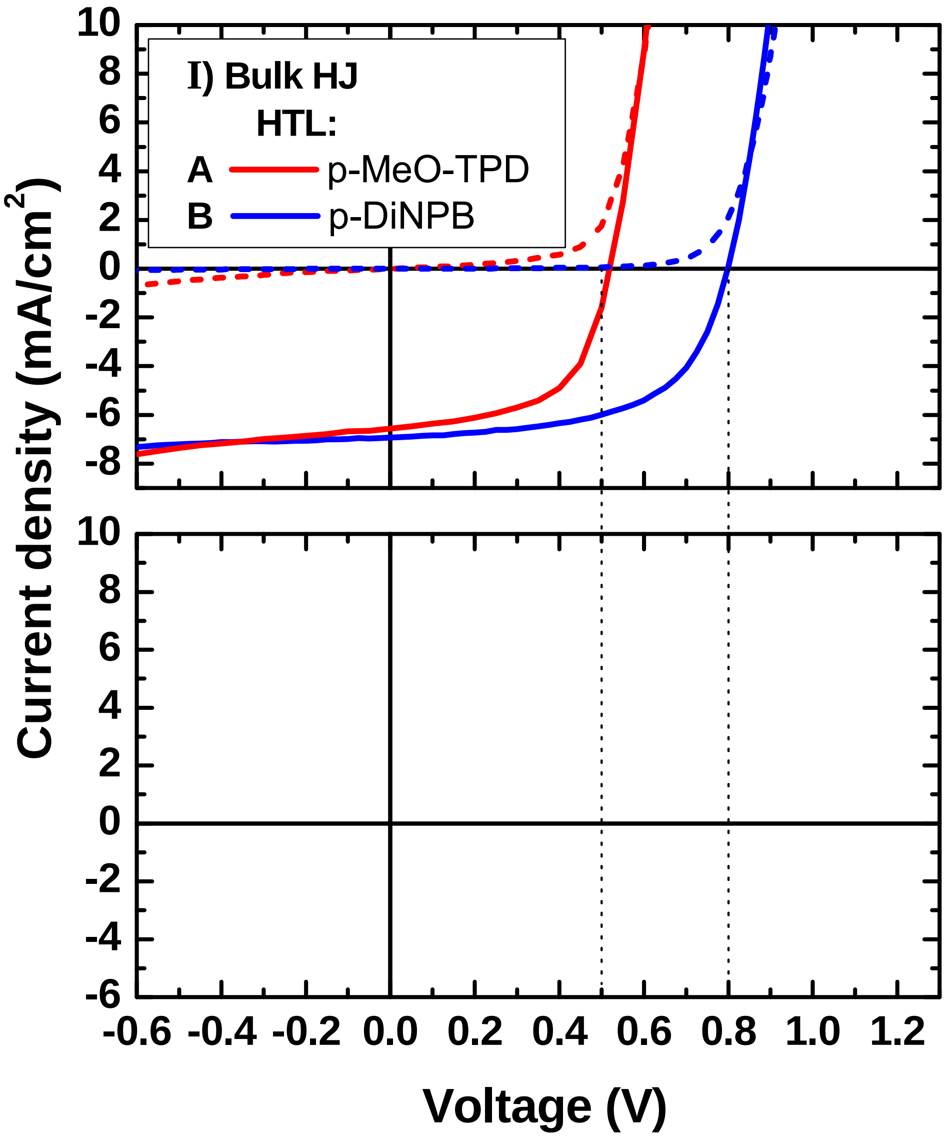
V_{OC} cannot exceed V_{bi} significantly

bulk HJ with p-MeO-TPD:

$$V_{bi} \approx V_{OC} = 0.5V$$



Influence of hole transporter Fermi level on V_{oc}



I) bulk HJ

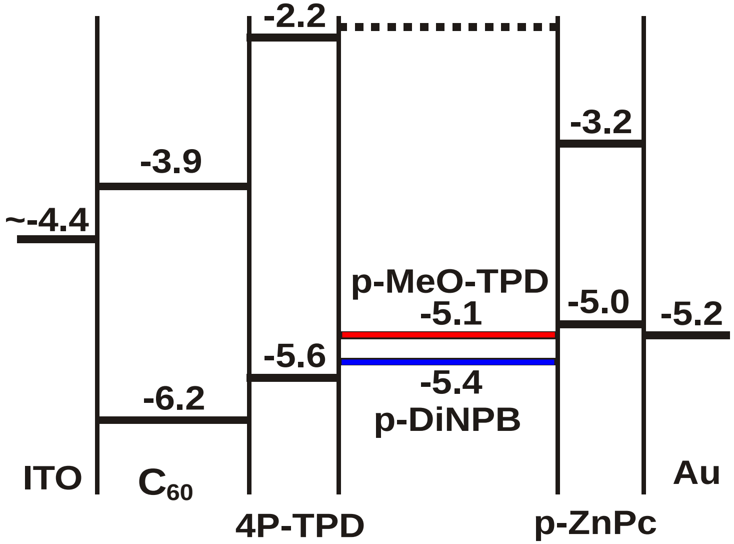
V_{OC} cannot exceed V_{bi} significantly

bulk HJ with p-MeO-TPD:

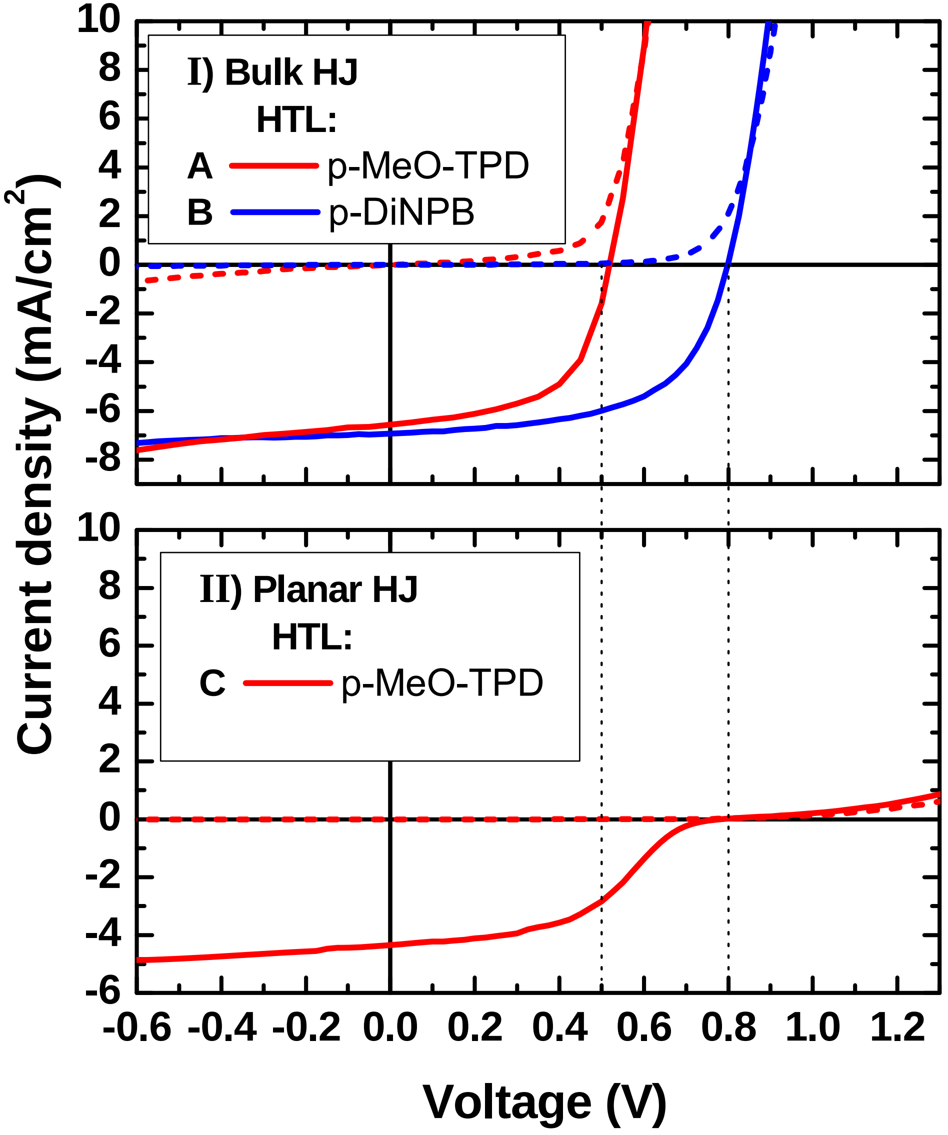
$$V_{bi} \approx V_{OC} = 0.5\mathrm{V}$$

bulk HJ with p-DiNPB:

$$V_{bi} \approx V_{OC} = 0.8\mathrm{V}$$



Comparison bulk vs. Planar heterojunction



I) bulk HJ

V_{OC} cannot exceed V_{bi} significantly

bulk HJ with p-MeO-TPD:

$$V_{bi} \approx V_{OC} = 0.5V$$

bulk HJ with p-DiNPB:

$$V_{bi} \approx V_{OC} = 0.8V$$

I) planar HJ

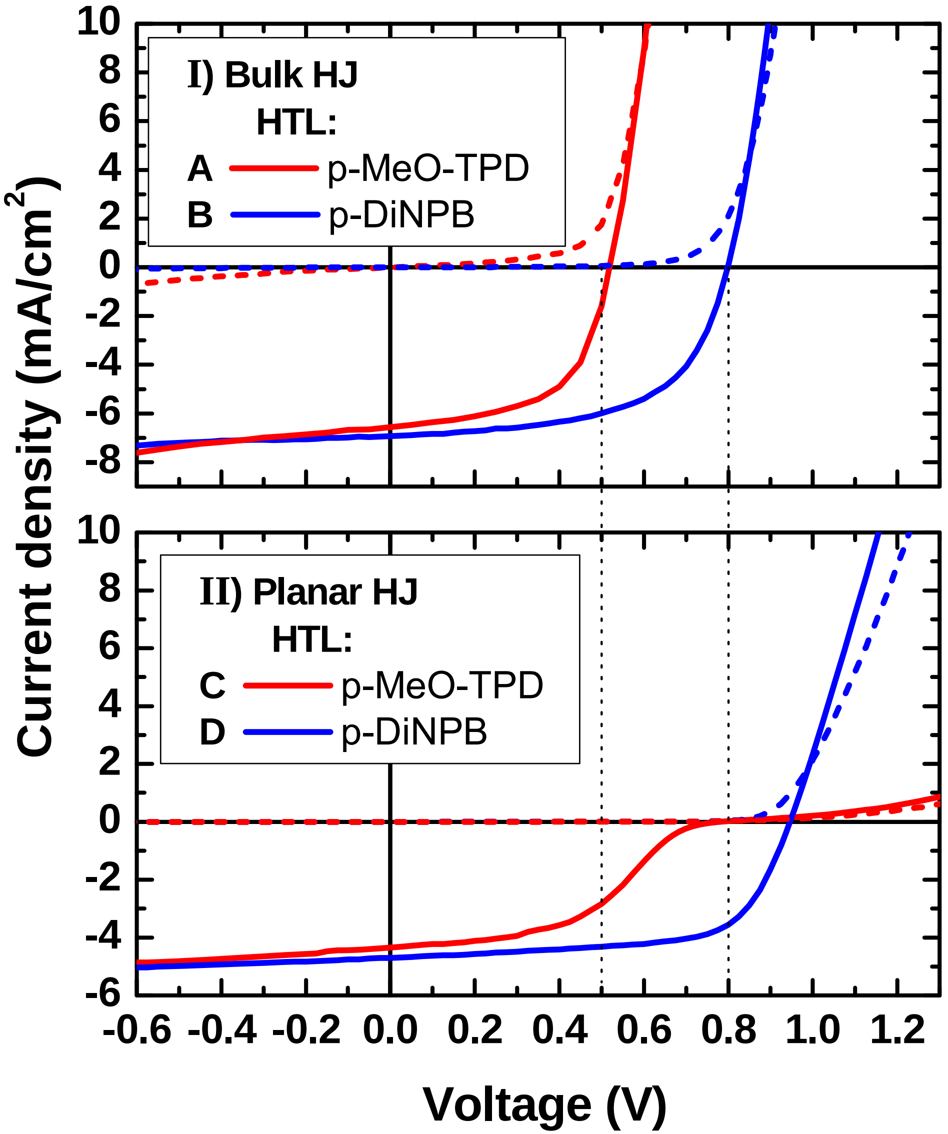
$$V_{OC} = E_{F,n} - E_{F,h} = E_g - kT \cdot \ln \frac{N_C N_V}{n_n n_p}$$

V_{OC} is predominantly determined by E_g

$$E_g = E^{LUMO}_{acceptor} - E^{HOMO}_{donor}$$

S-shape due to comp. low V_{bi} and barrier (HTL/4P-TPD)

Influence of hole transporter Fermi level on V_{oc}



I) bulk HJ

V_{OC} cannot exceed V_{bi} significantly

bulk HJ with p-MeO-TPD:

$$V_{bi} \approx V_{OC} = 0.5\mathrm{V}$$

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$$V_{OC} = E_{F,n} - E_{F,h} = E_g - kT \cdot \ln \frac{N_C N_V}{n_n n_p}$$

V_{OC} is predominantly determined by E_g

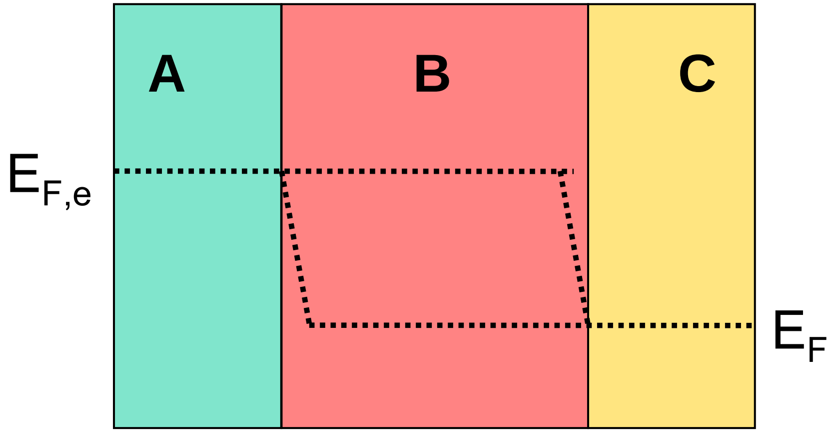
$$E_g = E^{LUMO}_{acceptor} - E^{HOMO}_{donor}$$

S-shape due to comp. low V_{bi} and barrier (HTL/4P-TPD)

increased V_{bi}
-> no S-shape, high FF (66%), high V_{OC} (0.95V)

The 3 steps to high voltage according to the Würfel picture

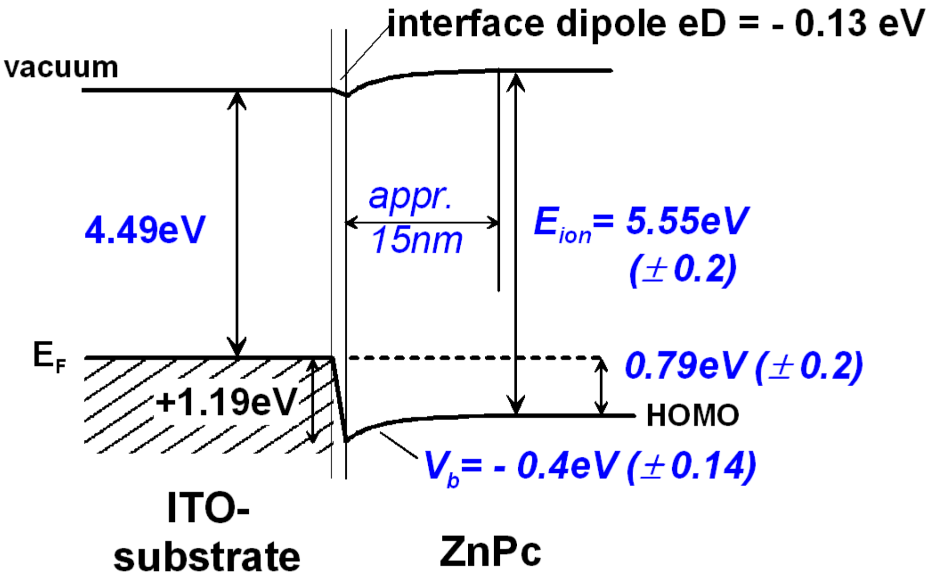
1. Quasi-Fermi-levels $E_{F,e}$ and $E_{F,h}$must be well separated in absorber
   $\Rightarrow$ excitons must be efficiently separated in absorber with little energy loss

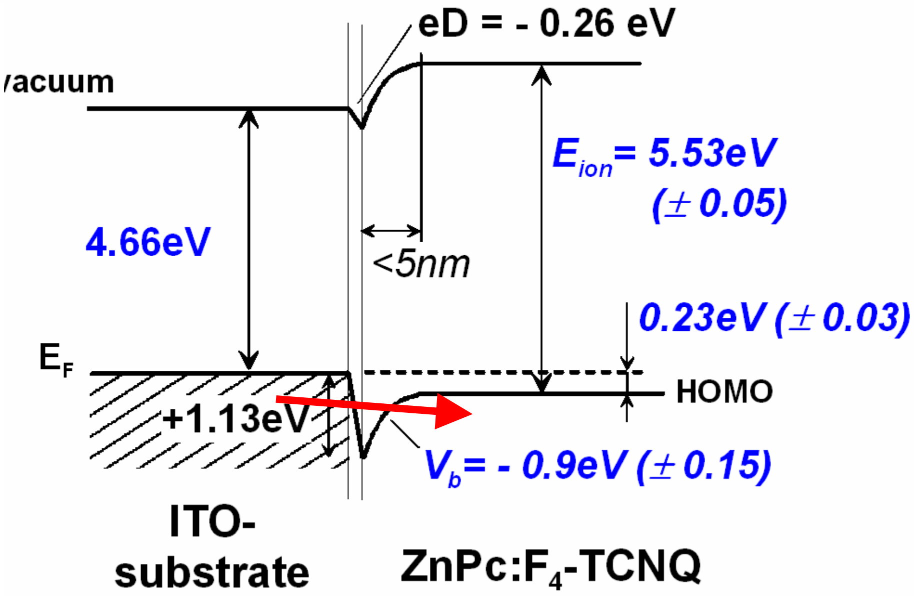


2. Quasi-Fermi-levels must be „picked up“ well by transport layers A and C

3. Energy loss at contact to electrodes must be avoided

Creation of ohmic contacts by doping



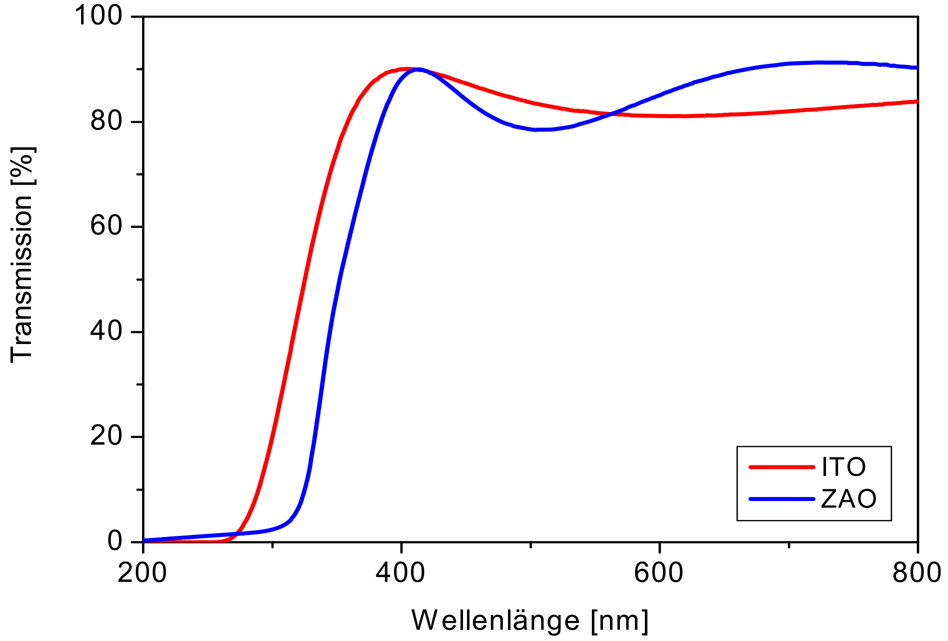


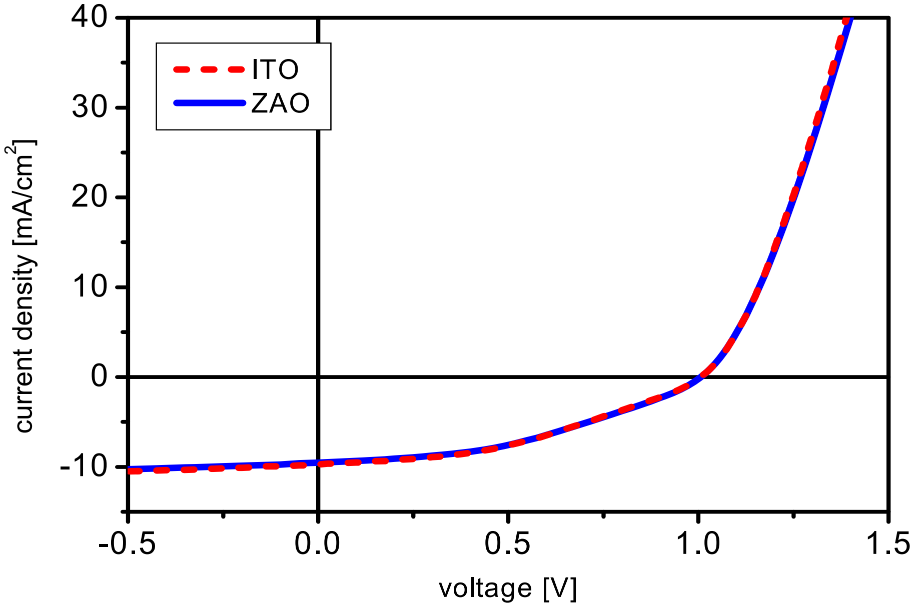
undoped : blocking

doped : ohmic

J. Blochwitz et al., Organic Electronics **2**, 97 (2001)

Example: Replace ITO by ZnO





- IV-characteristic of both devices comparable

- same open circuit voltage V_{oc}: work function of TCO does not influence the V_{oc}

	j_{sc} [mA/cm²]	V_{oc} [V]	FF	η * [%]
ITO	6.35	1.01	0.4	2.6
ZAO	6.06	1.01	0.41	2.5

*a spectral mismatch between sun simulator and AM 1.5 spectra was taken into account

K. Schulze et al., Appl. Phys. Lett. **91**, 073521 (2007)

Conclusions on the voltage

- Optimized energy step at heterojunction is crucial
- V_{oc} can exceed V_{bi} in organic solar cells
- However, there are limits: diffusion requires large carrier gradient:
  excessive recombination near the photoactive zone
- Doped transport layers allow high V_{bi} and virtually any contact material

Outline

- Some thoughts about Organic PV in general
- Status of small-molecule organic solar cells:
  key innovations in the past
- Future challenges:
  - understanding and increasing the voltage
  - covering the entire solar spectrum: IR & tandem cells
  - stability
- Low-cost manufacturing

Extending absorption to the infrared: SnPc

APPLIED PHYSICS LETTERS 87, 233508 (2005)

Organic solar cells with sensitivity extending into the near infrared

Barry P. Rand, Jiangeng Xue,[a] Fan Yang, and Stephen R. Forrest[b]
Department of Electrical Engineering and Princeton Institute for the Science and Technology of Materials (PRISM), Princeton University, Princeton, New Jersey 08544

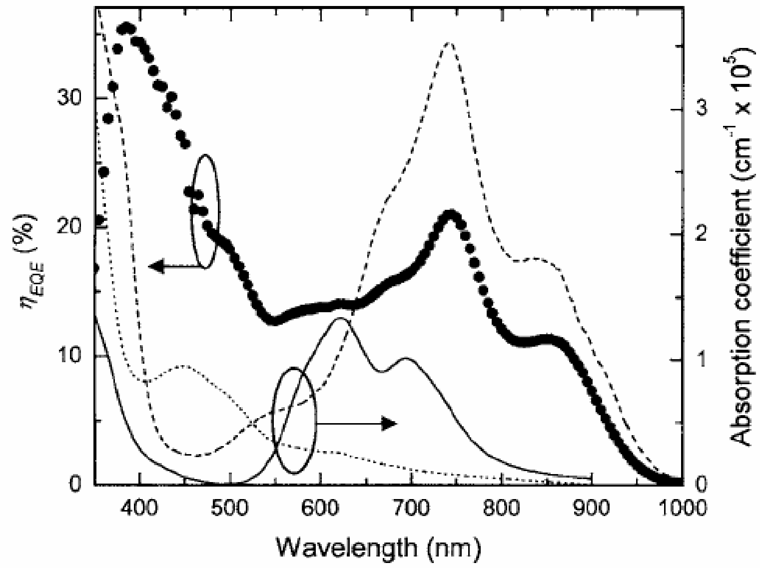


FIG. 3. Measured external quantum efficiency (η_{EQE}) spectrum (filled circles) for the device of Fig. 1. The absorption coefficients of CuPc (solid line), a 50-Å-thick film on SnPc (dashed line), and C_{60} (dotted line) are also shown

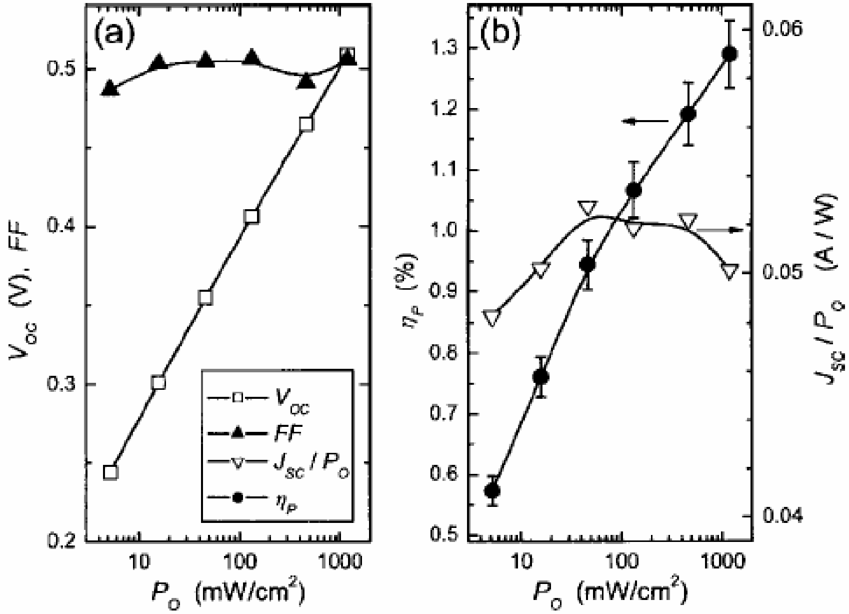
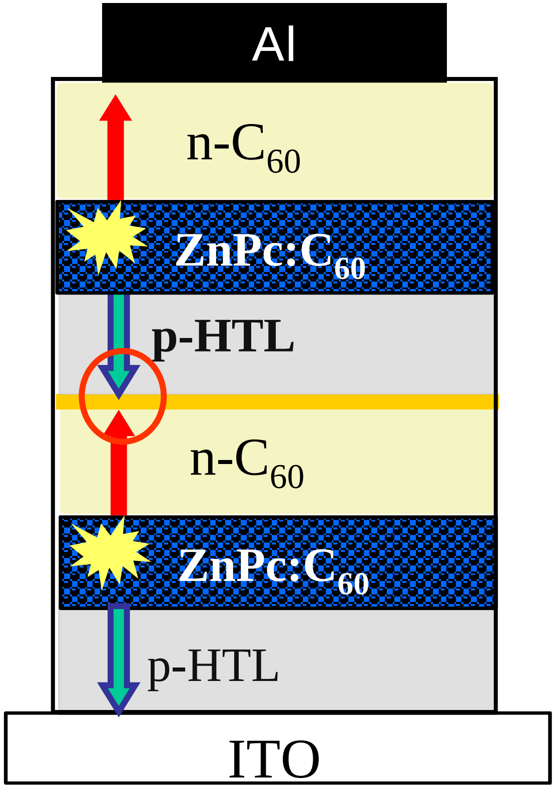
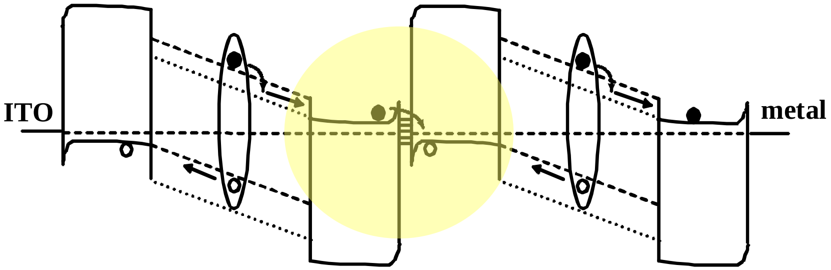


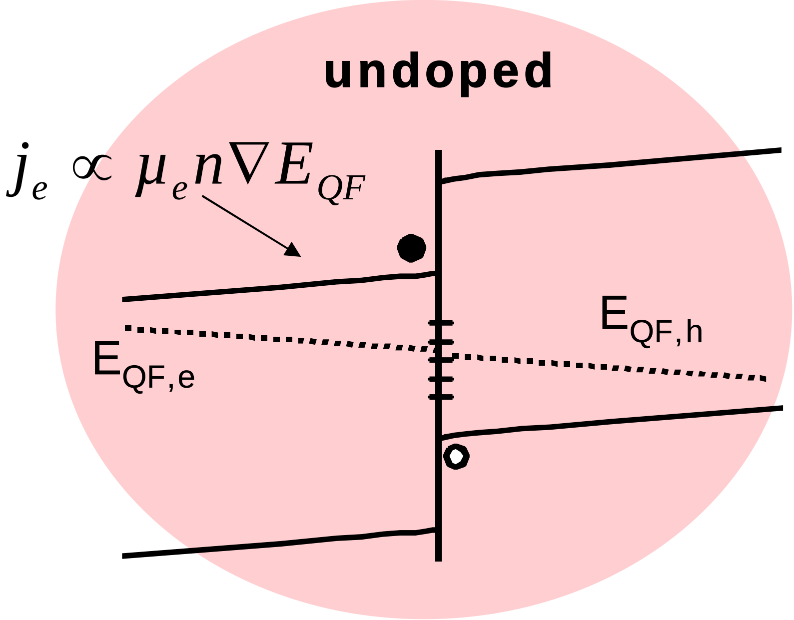
FIG. 2. (a) Fill factor (FF), open-circuit voltage (V_{OC}), (b) responsivity (J_{SC}/P_0), and power conversion efficiency (η_P) of devices with the same structure as Fig. 1 under various AM1.5G standard solar illumination intensities, P_0. The solid lines serve as guides for the eyes.

Pin-tandem cells: charge recombination

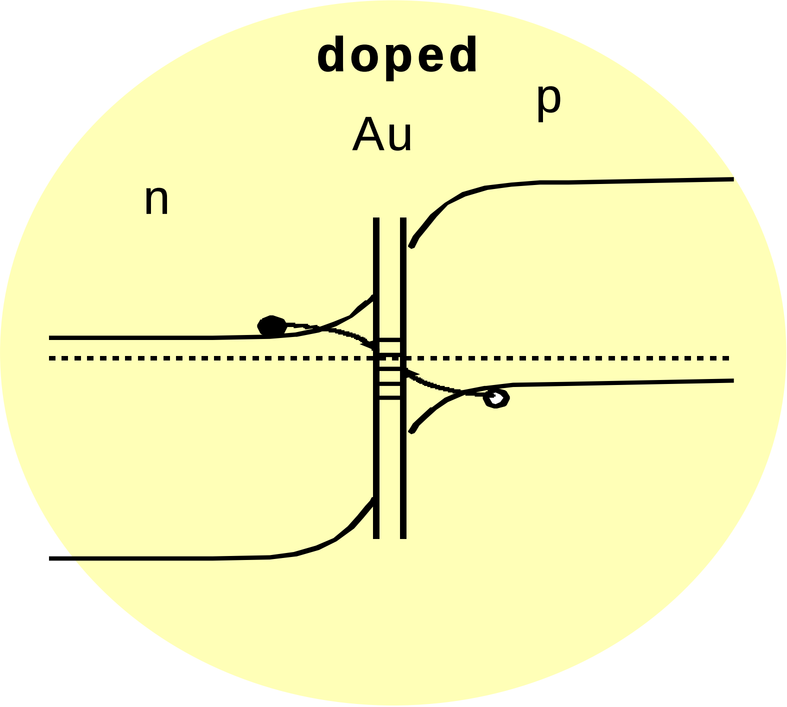


Doping is crucial for tandem cells: Interface recombination with minimum free energy loss

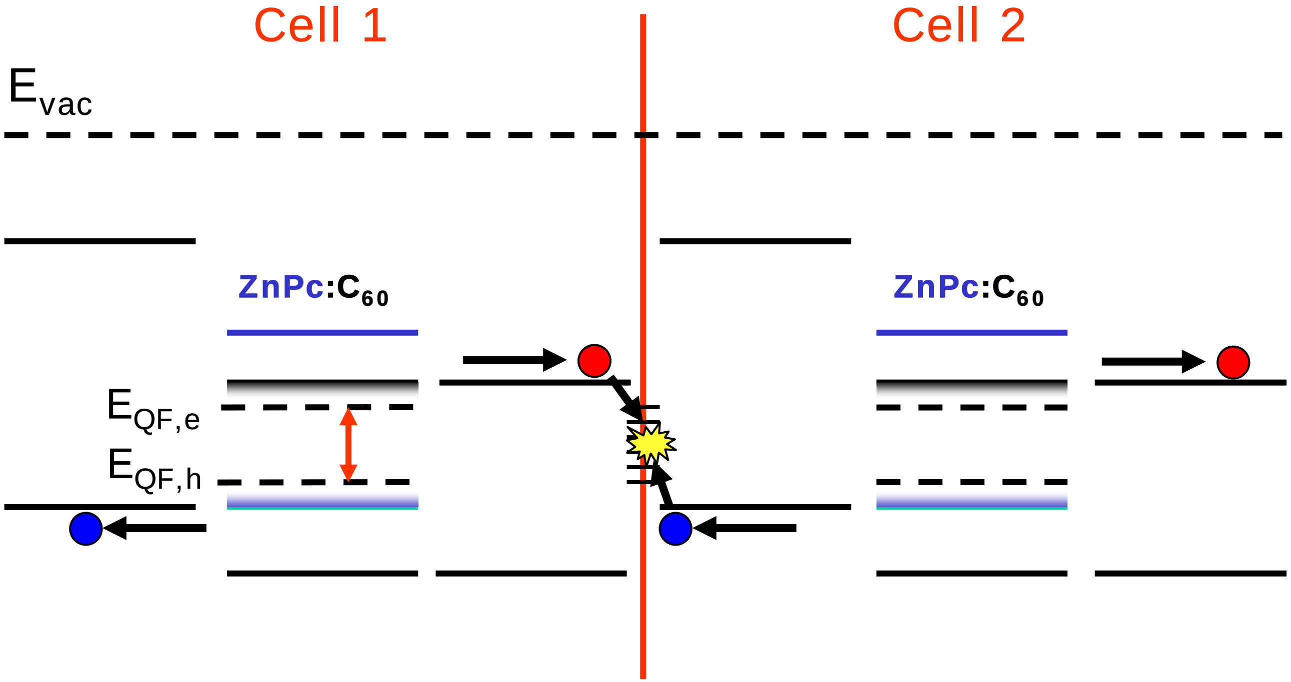




$j_e \propto \mu_e n \nabla E_{QF}$



Recombination without doping I

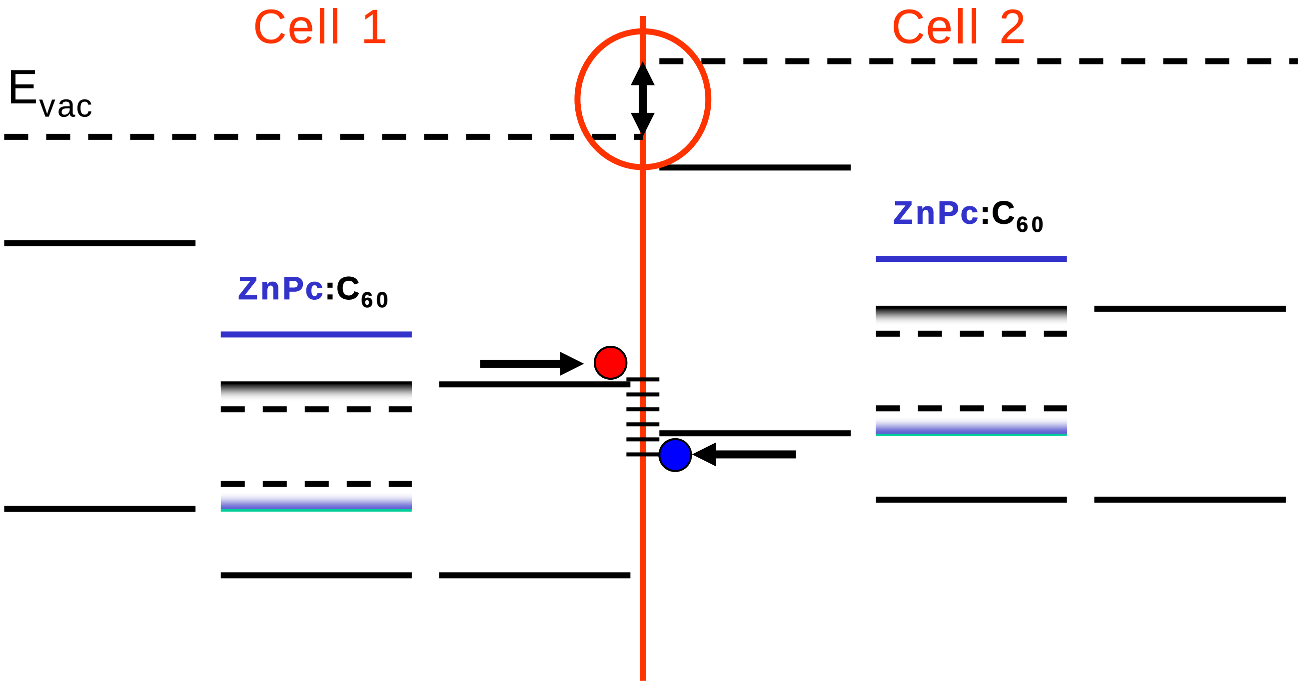


No doping, no interface dipole

➔Carrier pair transforms its complete energy into heat upon recombination

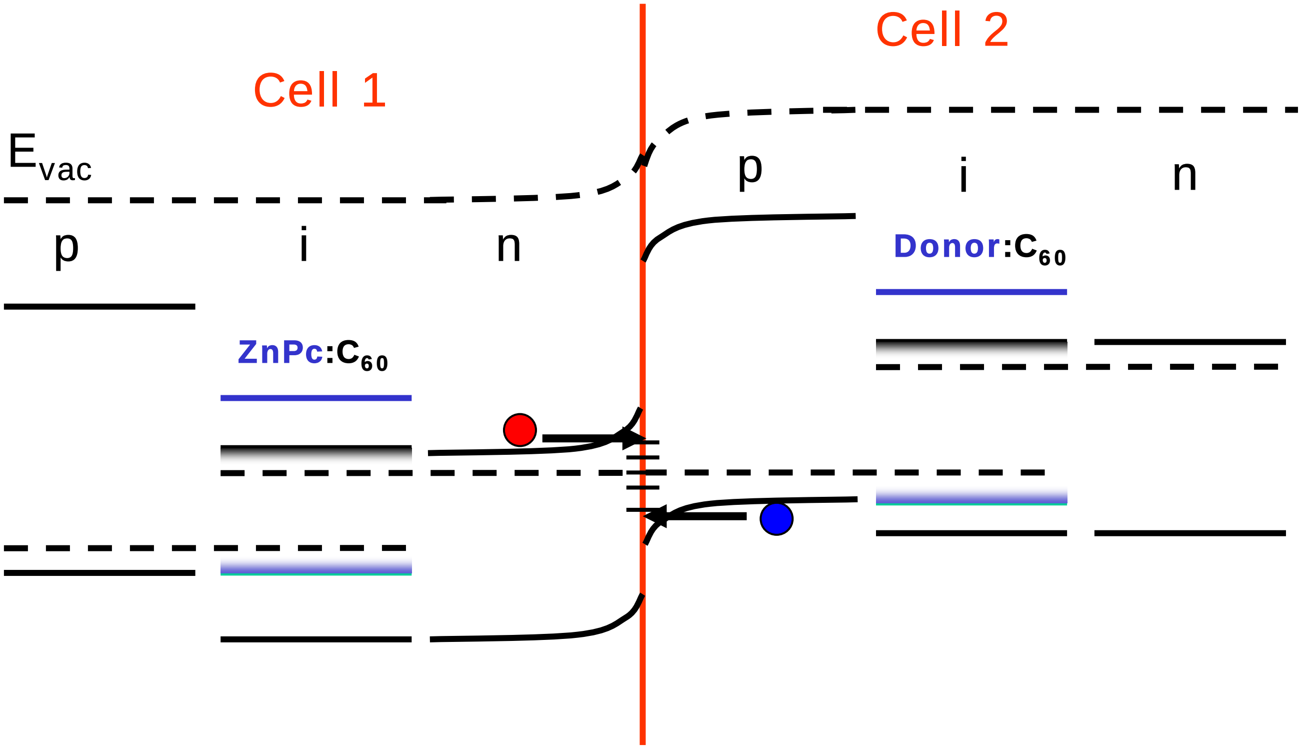
➔Recombination centers are not enough

Recombination without doping II



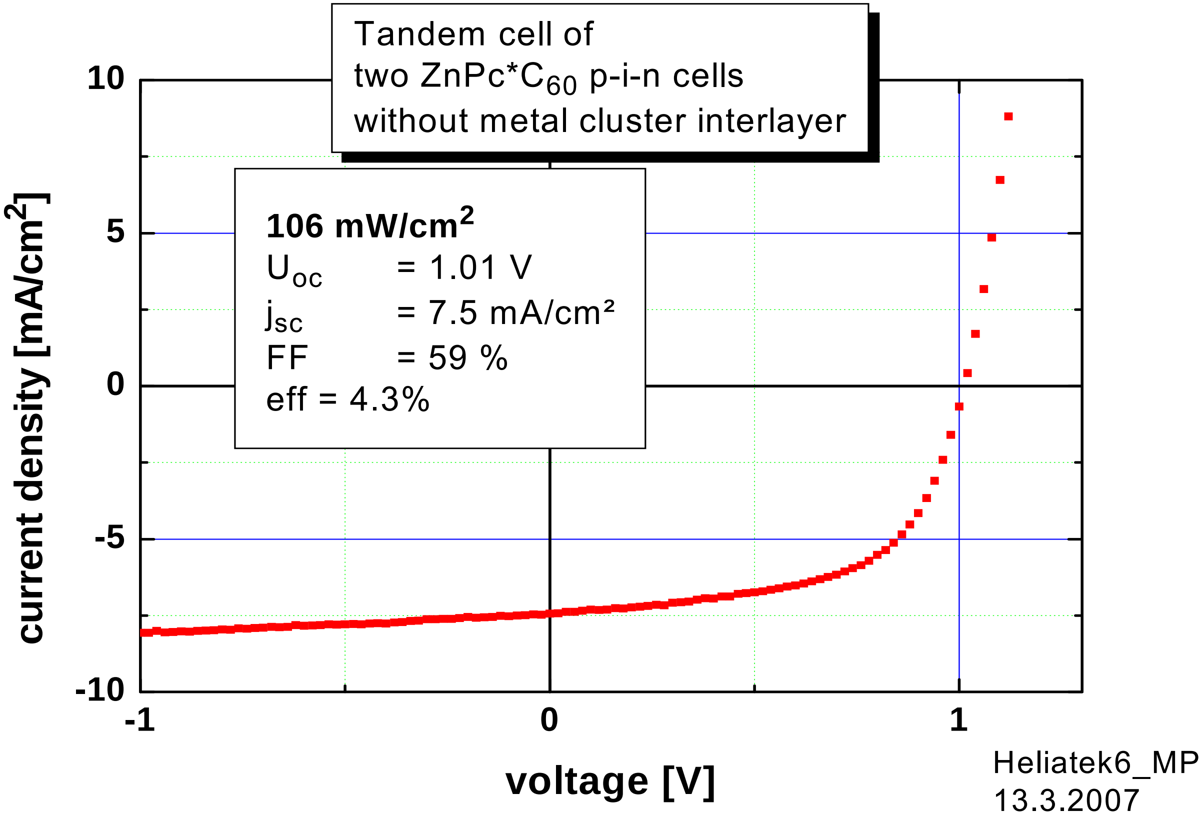
Lucky strike:
Formation of **suitable interface dipole** upon deposition of metal nanoclusters onto cell 1
➔Recombination may be loss free even without doping
cf. Yakimov, Peumans et al.

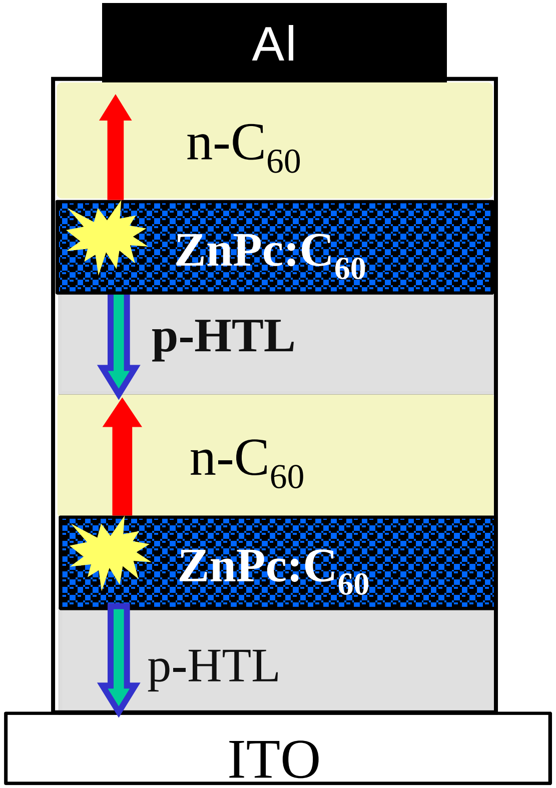
Recombination **with doping**



- Minimum energy loss by alignment of Fermi levels
- Gold clusters not needed
- R. Timmreck et al. unpublished

ZnPc/C_{60} tandem cell (IAPP&Heliatek 2007)





- Interface between subcells without metal clusters
- direct contact between p-doped and n-doped layer

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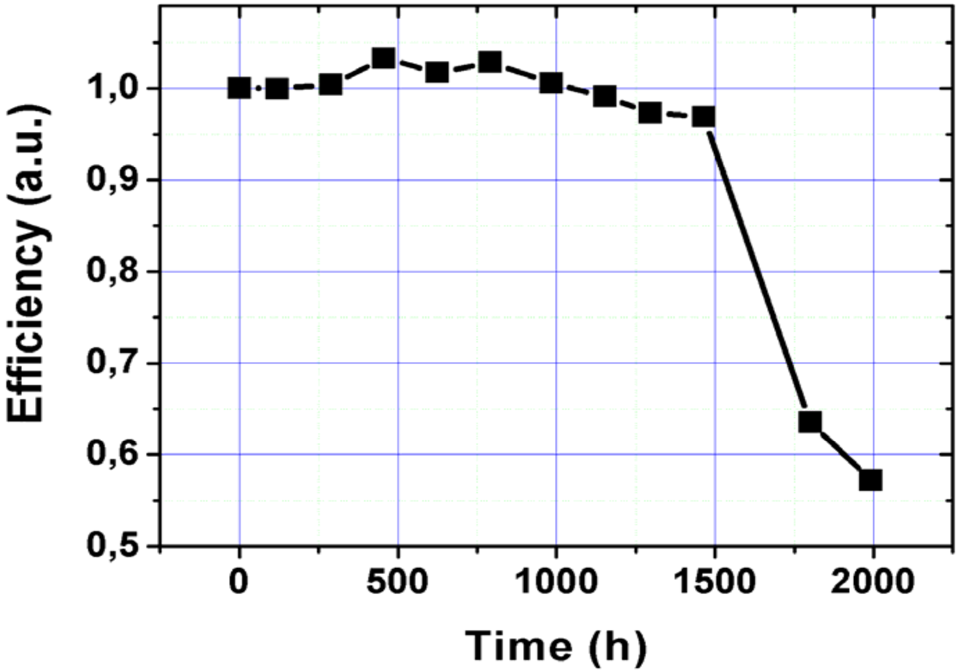
Long-term stable tandem cells

heliatek
Organic based Photovoltaics

Encapsulated sample for **1000h** under halogene lamp at **50°C;**
intensity corresponds to approx. **2 suns**:
- V_{oc} , j_{sc} and saturation factor ($j(-1V)/j_{sc}$) perfectly stable
- FF reduced from 60% to 58%

Extrapolated lifetime (80%):
~ 10 000h
at 100mW/cm², 50°C

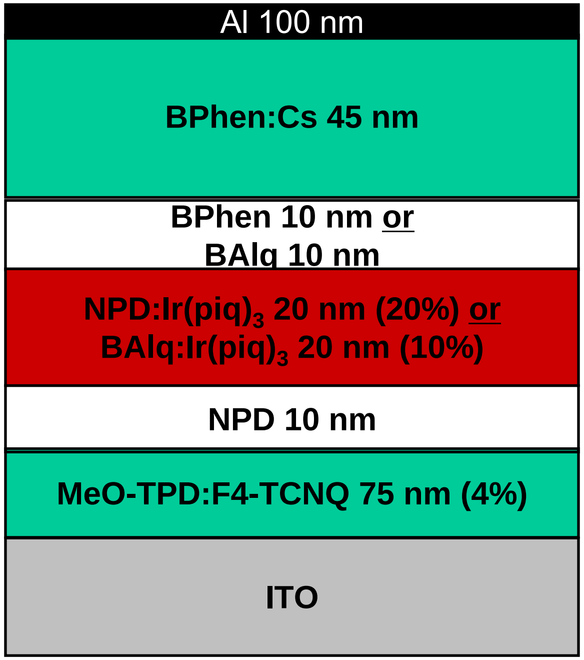


However:
Rapid degradation beyond 1500h together with color change in epoxy resin
➔ probably breakdown of encapsulation

R. Franke et al. Solar Energy Materials & Solar Cells, in press

Case Study: Ultra-Stable deep red pin OLED

- Phosphorescent red pin OLED using „open“ materials
- Different hosts (NPD, Balq) and blockers (Balq, Bphen)
- All materials very carefully sublimed (Creaphys sublimator)



Al 100 nm

BPhen:Cs 45 nm

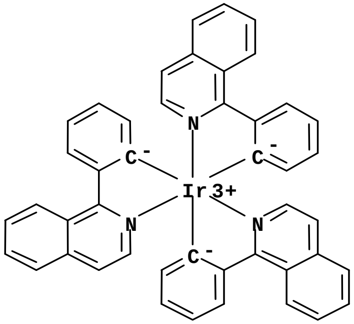
BPhen 10 nm or
BAlq 10 nm

NPD:Ir(piq)$_3$ 20 nm (20%) or
BAlq:Ir(piq)$_3$ 20 nm (10%)

NPD 10 nm

MeO-TPD:F4-TCNQ 75 nm (4%)

ITO

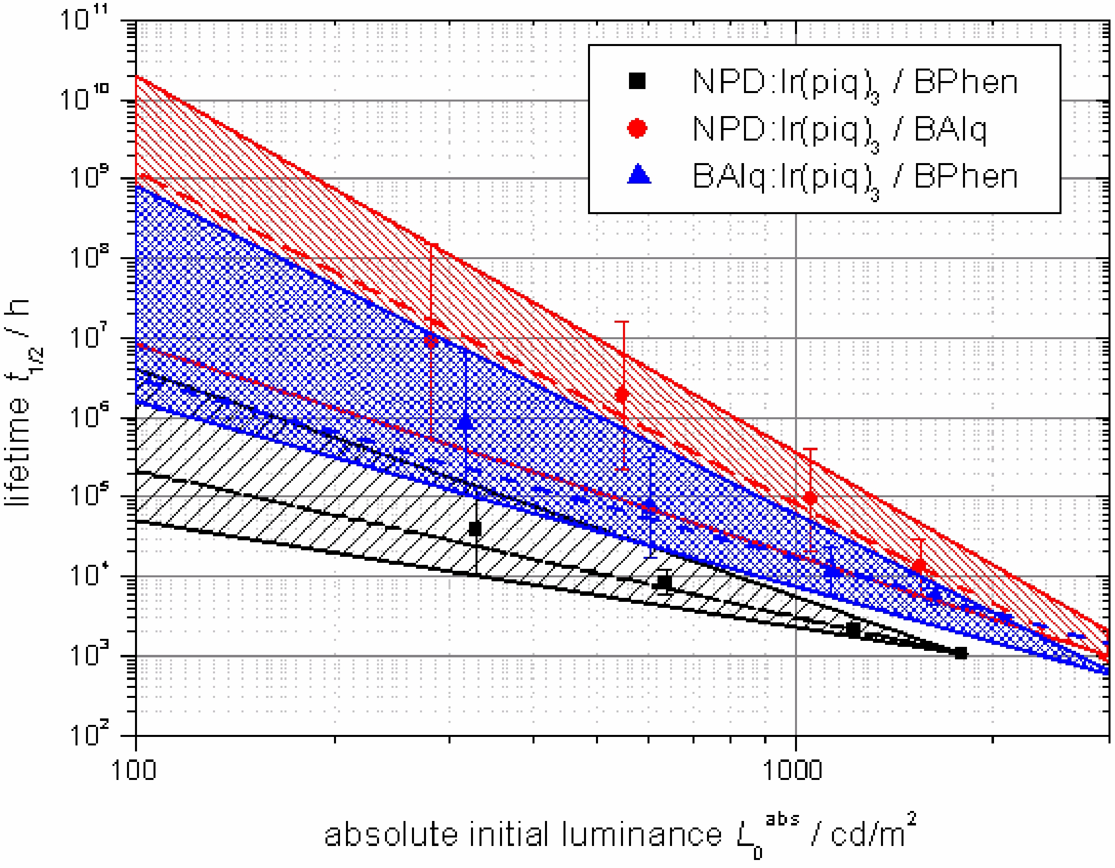


Ir(piq)$_3$ deep red
CIE 0.68, 0.32

R. Meerheim et al., Appl. Phys. Lett. **89**, 061111 (2006)

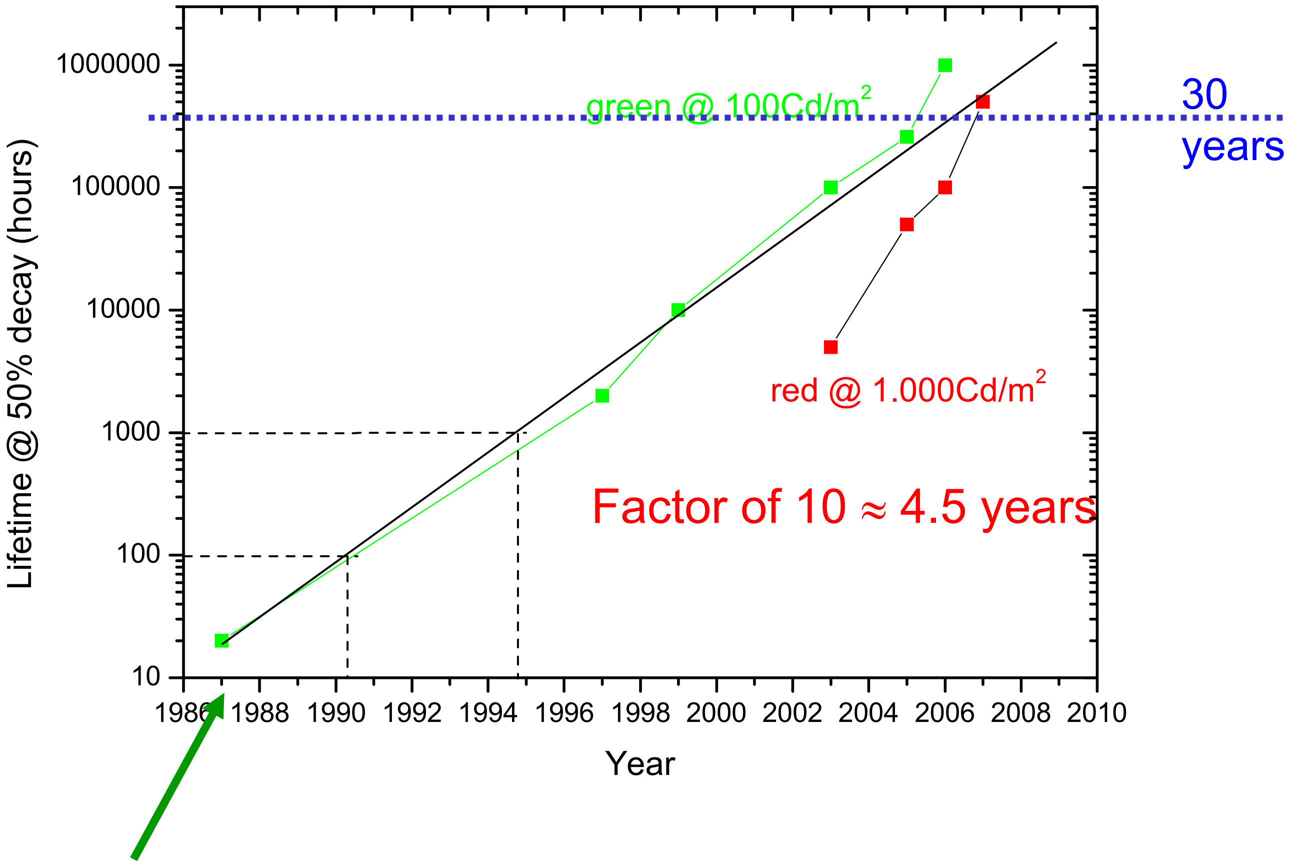
Ultrastable red OLED: Lifetimes well beyond 10Mhrs @100Cd/m^2

- Already the lower limits $\delta^{-} t_{1/2}^{SED}$ gives **10 million hours** lifetime at 100 cd/m^2
- One Emitter molecule runs through $2.4 \cdot 10^{11}$ photocycles
- BAlq/BAlq devices „decay“ even slower



R. Meerheim et al., Appl. Phys. Lett. **89**, 061111 (2006)

OLED lifetime: It never stops to grow



Factor of 10 ≈ 4.5 years

Tang& vanSlyke 1987

- Solar cells should do better:
- Lower gaps
- Excitons are separated quickly

Outline

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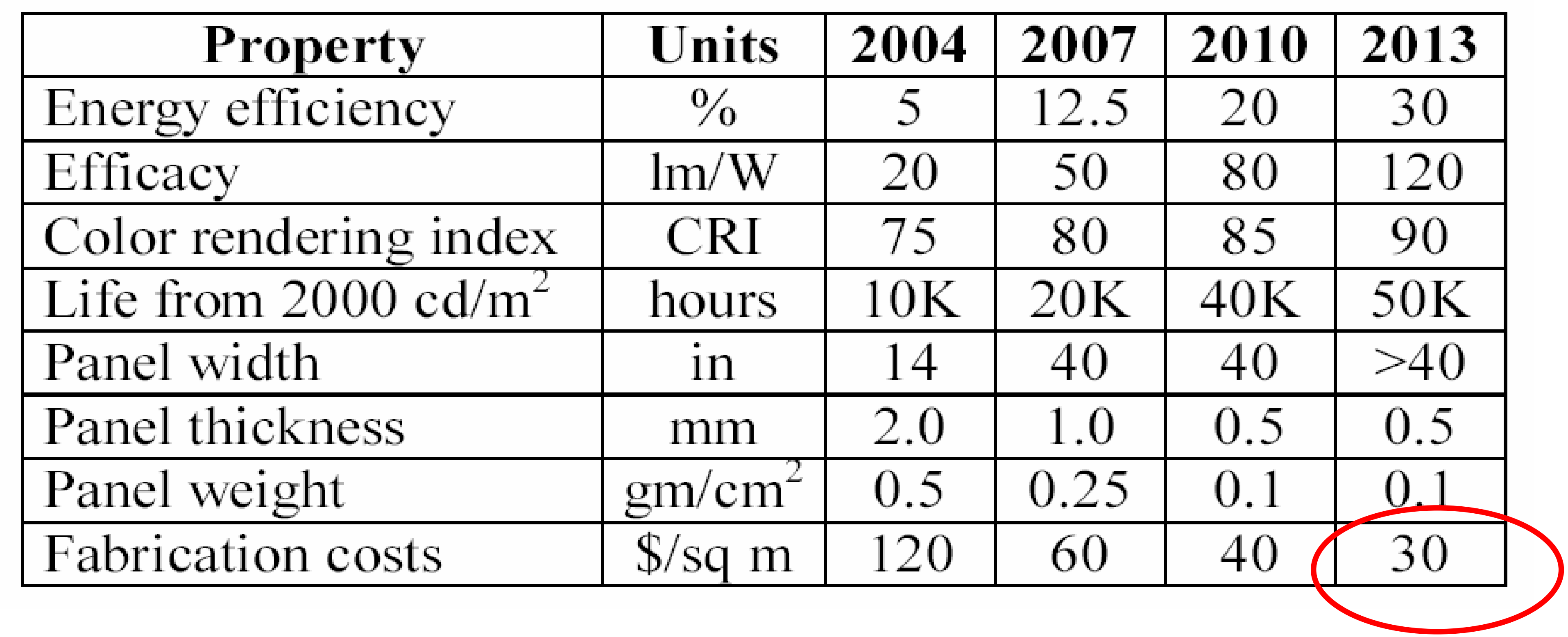
Helpful: Comparison to Lighting

IPMS

Fraunhofer Institut
Photonische
Mikrosysteme

OLED lighting: Technology Roadmap (USDC)



Property	Units	2004	2007	2010	2013
Energy efficiency	%	5	12.5	20	30
Efficacy	lm/W	20	50	80	120
Color rendering index	CRI	75	80	85	90
Life from 2000 cd/m^2	hours	10K	20K	40K	50K
Panel width	in	14	40	40	>40
Panel thickness	mm	2.0	1.0	0.5	0.5
Panel weight	gm/cm^2	0.5	0.25	0.1	0.1
Fabrication costs	$/sq m	120	60	40	30

30 \$/m^2 = 0.3 Cent/cm^2 ≈ 30 Cent/pWatt !

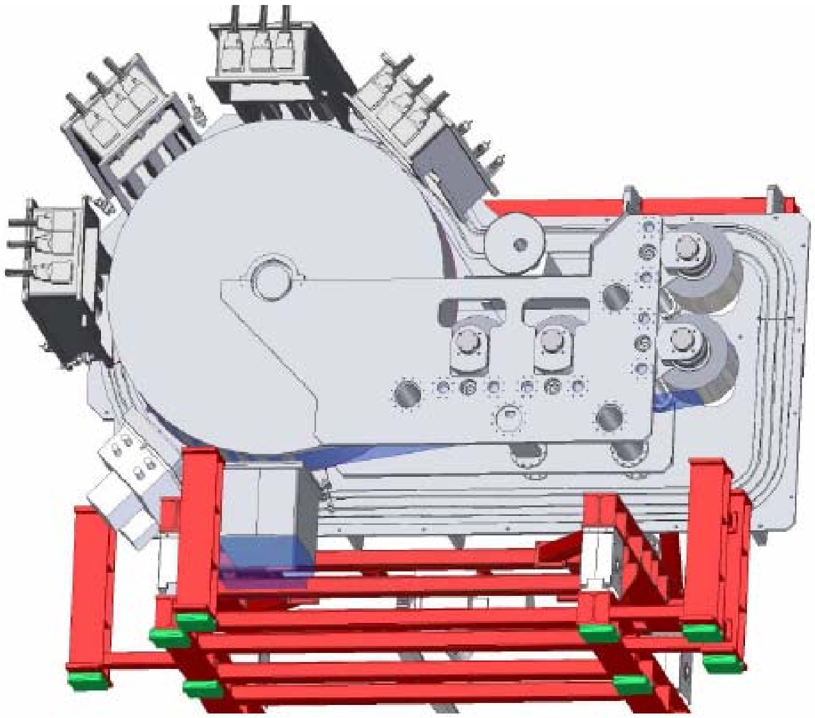
OLED lighting cost ≈ organic solar cell cost !

New funding project: Roll-to-roll coating for small-molecule OLED

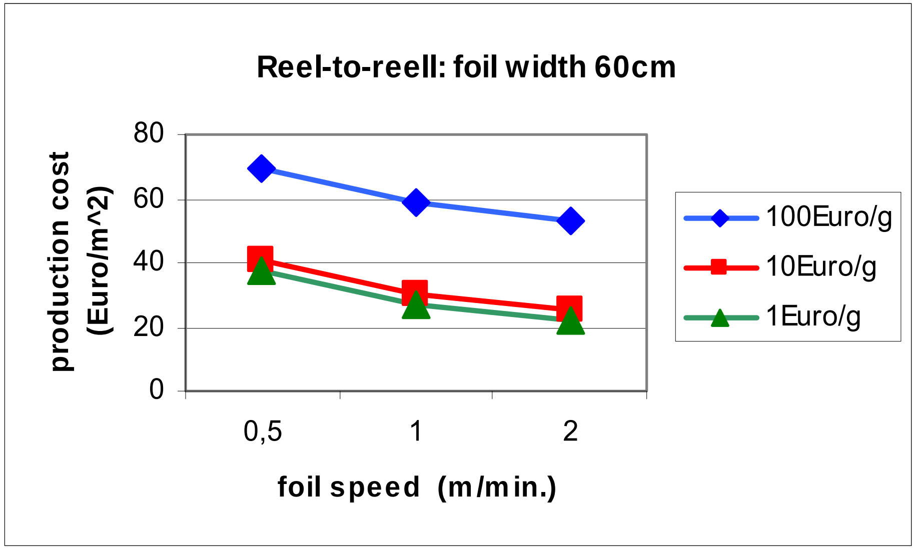
Partners:

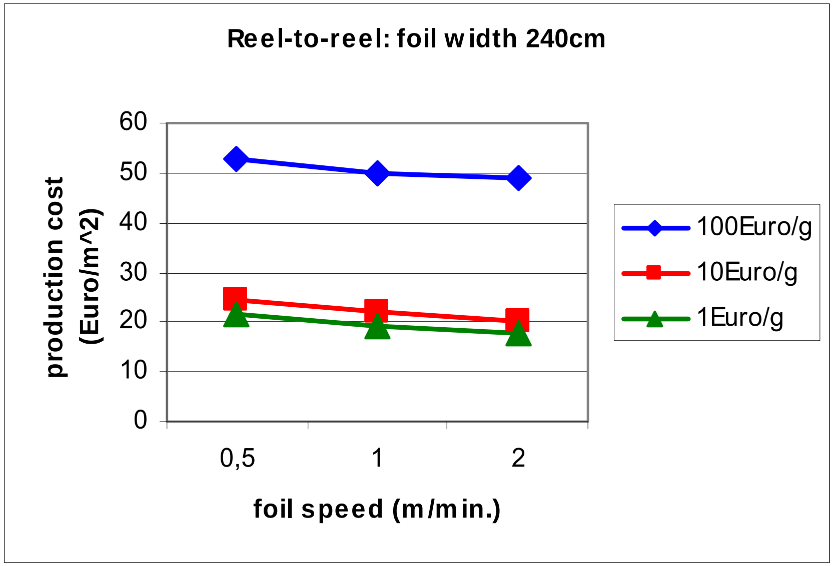
ROLLEX

- TU Dresden
- FhG-IPMS Dresden
- Novaled
- Laytec
- Von Ardenne
- Philips



Coating cost for roll-to-roll tool





- Cost of below 20€/m^2 is achievable (materials limited)
- Organic Costs below 10€/g needed
- Cost for Encapsulation/Cathode is critical

Organic Valley

The region of Dresden is Europe's largest cluster for organic semiconductor R&D and manufacturing. More than 10 companies with over 400 employees (2008) are active in this exciting and quickly growing new technology. This website is meant to give an overview about the topics. Further information may be obtained from the listed partners or directly from Prof. Dr. Karl Leo.

Enjoy browsing this site!

Last update:
January 07. 2008 17:40:44

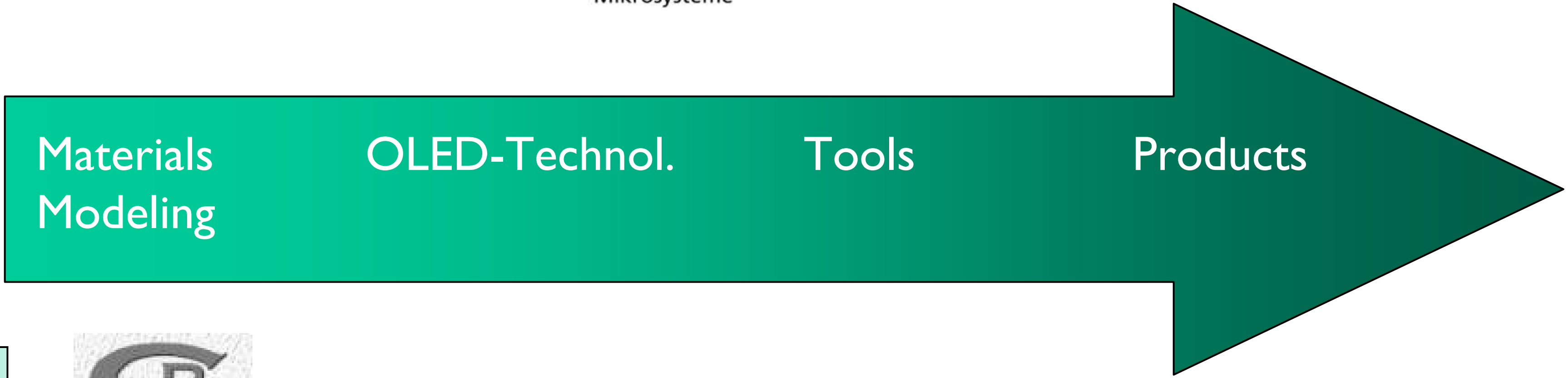
Organic Value Chain in Saxony
www.organic-valley.org

R&D

iapp

Fraunhofer IPMS
Institut
Photonische
Mikrosysteme

COMEDD



Materials
Modeling

OLED-Technol.

Tools

Products

Industry

CreaPhys

sim tec

novaled

VON ARDENNE

MED
MicroEmissive Displays

heliatek
Organic based Photovoltaics

Plastic Logic

More than 500 people in 2008!

Conclusions

Small-molecule organic solar cells are a promising technology, but:

- Efficiency way too low to achieve broad application
- Materials basis still extremely narrow
- Bulk heterojunction morphology is a challenge
- Low-cost manufacturing technologies possible

Acknowledgment

- G. Schwartz, K. Fehse, Q. Huang, S. Reineke, R. Schüppel, F. Lindner, K. Walzer, G. He, X. Zhou, J. Huang, A. Werner, J. Drechsel, F. Kozlowski, K. Schulze, C. Uhrich, R. Lessmann, T. Müller, J. Meiss, K. Harada, M.K. Riede, T. Fritz (IAPP)
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- BMBF, SMWA, SMWK, DFG, EC, FCI, NEDO

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